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Analysis of Soldier Radio Waveform Performance in Operational Test

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Executive Summary

The Soldier Radio Waveform (SRW) is a Joint Tactical Radio System (JTRS) networking software that aims to provide voice, data, and video capabilities to small combat units and unmanned systems. SRW is the cornerstone of the Army's lower tier tactical network. Up to a quarter of a million radios, at a cost of several billion dollars, are expected to run SRW. Recent operational test events of the system have demonstrated several deficiencies, including poor range compared to legacy systems, excessive power consumption, and a high level of network and spectrum management that may not be operationally feasible. These issues are not unique to SRW, but rather have plagued the mobile ad-hoc network (MANET) systems under development for the last decade. In this report, we begin with a discussion of our observations from operational test, which inform the focus of our analytic and simulation work. We then present an analysis of the technical implications of the many discrepancies between the Army's use of SRW and the original concept with which the waveform was designed. We used our observations from the Network Integration Exercises (NIEs) to construct representative scenarios for simulation and to configure the SRW nodes according to the Army's implementation. Finally, we present the results of our modeling and simulation of SRW, which we use to explain root causes for symptoms we have seen in operational test.

We explore two main areas of SRW operation using modeling and simulation: the overhead traffic associated with network maintenance and its implications for network size and performance; and the operation of the Combat Net Radio (CNR) voice application. Network maintenance traffic (overhead) in MANETs significantly limits scalability, which has motivated the Army to limit SRW nets to approximately 30 nodes – 4 percent of the 800+ node network that SRW was originally designed to form. The major network architecture changes forced by this bandwidth-crippling overhead has in turn produced a cascading negative effect on network robustness, management, and spectrum availability, which we have studied in detail in this analysis. CNR is an application that replicates the type of legacy voice network offered by Single Channel Ground-to-Air Radio System (SINCGARS), while also providing range extension through a configurable number of neighbor node radio-frequency (RF) relays. We find that the CNR's multiple relay retransmissions of the same call may increase the difficulty of signal processing, potentially hurting rather than helping, call quality. We present a detailed review of this capability, including its sensitivity to terrain and the relative positions of relay nodes.

These SRW-specific results are integrally related to the generic propagation challenges that face MANETs and that IDA has studied extensively in the past. We review some basic concepts of radio attenuation and apply our findings to specific test results seen in NIE. In particular, we find that attenuation due to urban blockages, coupled with the known thresholds for quality links in SRW may make communication from outside to inside of buildings unreliable (as seen in NIE 14.1). We finish this section with a detailed discussion of power consumption issues, outlining potential hardware and software modifications to reduce the likelihood of radio failure and soldier injury.

Finally, our investigation into SRW's design and implementation also led us to question why some of SRW's most critical features – including its electronic warfare (EW) mode – has been largely absent from operational test. A section of this report is dedicated to a discussion about this important feature. We conclude that the expectations for SRW protection against electronic warfare attacks must be reevaluated and a new direction established, if the waveform is to provide adequate protection to the warfighter in hostile environments.

Through this complementary methodology of observing operational test, analyzing the fundamental limitations of the technology, and modeling and simulation, we have traced the vast majority of reported issues, including lack of consistent connectivity, low throughput, excessive power consumption, limited spectrum availability, and an increased network planning burden to SRW. Some of these are rooted in actual shortcomings of the waveform, while others reflect a disparity between the waveform's original concept and its implementation on specific radio platforms and in specific network topologies. We found that many of the core challenges and their root causes are shared by other aspects of the tactical network, which indicate a systemic problem in the technology design and implementation.

Contents

1. Introduction

A. What is SRW?

The Soldier Radio Waveform (SRW) is a Joint Tactical Radio System (JTRS) networking software that aims to provide voice, data, and video capabilities to small combat units and unmanned systems. It was originally designed for three domains: Soldier System (SS), Unattended Ground Sensor/Intelligent Munitions Systems (UGS/IMS), and Non-Line of Sight – Launch System (NLOS-LS).[1] This report focuses on the SS domain, where SRW supports combat communications between dismounted soldiers and their support ground and air vehicles. Interoperability with other, high-throughput networking waveforms, such as the Wideband Networking Waveform (WNW), is also a key aspect of SRW design, so that it can ultimately extend its information exchange to the broader battlefield network.

SRW is designed to operate as a mobile ad-hoc network (MANET), enabling communication through a self-configuring, infrastructure-less network of mobile nodes. In the SS domain, these nodes, operating in the frequency range 225-2500 MHz, form the two-tier network architecture depicted in Figure 1-1. The lower tier (1A) consists of multiple "islands" (these may be platoon- or squad-level nodes); the upper tier consists of island heads, tier 1B-only participants (company-level nodes), and internetwork gateways. The waveform's proactive routing protocol continuously monitors the connectivity of its member nodes, automatically reforming to accommodate lost or discovered nodes, and adaptively constructing optimal routing paths between mobile nodes.

SRW offers three modes of operation in the SS domain: Combat Communication (CC) mode, Electronic Warfare (EW) mode, and Featureless Low Probability of Intercept/Low Probability of Detection (LPI/LPD).[2] CC mode is the standard communication mode, offering the highest throughput rates and spectral efficiency. EW mode provides additional resistance to jamming and interference compared to CC albeit at reduced throughputs. Featureless LPI/LPD supports covert operations using low probability of intercept/low probability of detection techniques. In addition, SRW provides a push-to-talk (PTT) Combat Network Radio-like voice communication service for CC and EW modes, allowing users to participate in voice communication call groups.

[1] Neither UGS/IMS or NLOS-LS are currently in use. Future implementation plans remain uncertain.

[2] Featureless LPI/LPD does not appear to be implemented in current SRW waveform releases but may be planned for future versions.

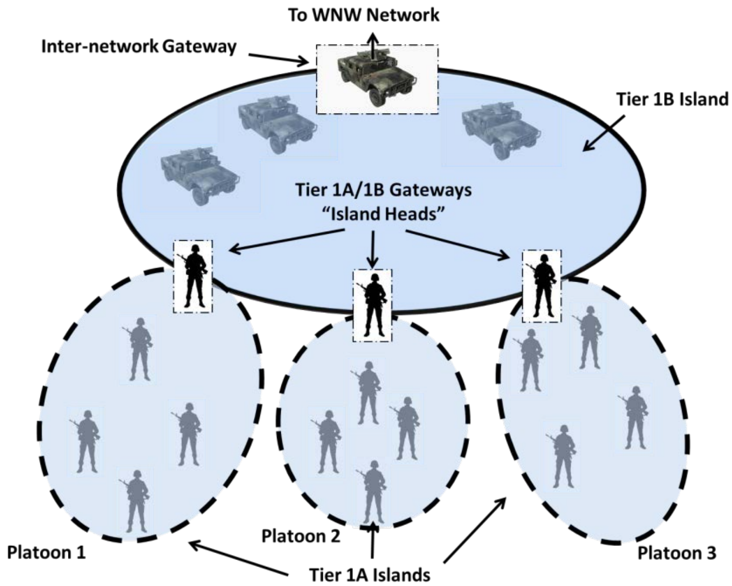

Figure 1-1. SRW Soldier System (SS) Network Topology

Tier 1A consists of multiple "islands" of nodes. "Island heads" provides a gateway to tier 1B, allowing data traffic to be routed between different islands. Dashed lines surrounding tier 1A islands show that island membership is fluid.

B. Operational Testing of SRW

SRW is a software package that has been ported to a variety of software defined radios (SDR) – some under development and others already available – and represents a critical component of the warfighter communications systems at the Network Integration Evaluation (NIE) and other operational test events. But because it is a virtual product, it is nearly impossible to separate performance of the software from the overall functioning of the radios that run it. During operational test, radios running SRW are configured with a cumbersome number of specific parameters[3] that further obfuscate the evaluation of the waveform. Most of the numerous output statistics produced by SRW are not transparent to the user and are characteristic of the many complex factors that drive networking, making it difficult to pin down a measure of success for operational effectiveness and suitability of each individual radio or link. In this report, we describe our efforts to use modeling and simulation to better understand the expected behavior of the software, the anomalies that are frequently observed by soldiers during test, and the types of metrics that are needed to evaluate SRW performance.

3 While we were unable to obtain the exact number of SRW parameters available to network planners, the SRW modeling and simulation (M&S) model used in this study offers dozens of adjustable parameters that control network formation (node discovery time, island affiliation metrics, topology change intervals), routing (maximum number of adjacencies, link-state advertisement intervals), route distribution, and link layer controls (link metric calculation parameters).

1. What Programs of Record Does SRW Affect?

SRW is an integral component of three tactical radios programs: Handheld, Manpack and Small-form Fit (HMS), Mid-tier Networking Vehicular Radios (MNVR), and Airborne, Maritime, Fixed Station (AMF). Over the next 10 years these radio programs may procure more than 250,000 SRW-equipped radios at a cost of several billion dollars.

a. Handheld, Manpack, and Small-Form Fit (HMS)

The HMS portfolio includes Rifleman Radio and Manpack, both of which use SRW to transmit information between ground vehicles and dismounted soldiers. Rifleman Radio is a lightweight, single-channel, dismount radio. HMS Manpack is a two-channel dismounted and vehicle radio that is designed to connect ground vehicle operators to the dismounted soldier.

While Manpack continues its fielding assessment, the Army is pursuing an interim solution known as SRW Appliqué. SRW Appliqué is a single-channel, vehicle-mounted radio that provides an SRW capability (essentially each vendor's version of the Rifleman Radio) coupled to current VRC-92 SINCGARS installations.

b. Mid-tier Networking Vehicular Radio (MNVR)

The MNVR radio is a vehicle-mounted system designed to extend communications from the squad to company, battalion, and brigade echelons. MNVR operates both SRW and WNW, allowing it to link the lower and upper tiers of the tactical network.

c. Airborne, Maritime, Fixed Station (AMF)

The AMF portfolio includes two systems that use SRW: the Small Airborne Link 16 Terminal (SALT) and the Small Airborne Networking Radio (SANR). Both SALT and SANR are software-defined radios designed to connect rotary-wing aircraft to ground units. SALT is being developed specifically for Apache aircraft and will run both Link-16 and SRW. SANR is being developed for a number of rotary aircraft including Apache, Chinook, Gray Eagle, Black Hawk, and Kiowa Warrior and will run SRW, SINCGARS, and WNW.

2. Why Does SRW Deserve the Level of Attention It Is Given in This Report?

Many of the issues we have observed are not unique to SRW, but rather have plagued the MANET systems under development for more than a decade. In fact, one could argue that SRW has met with more success than other waveforms in development. The WNW, the JTRS mid-tier networking software, has yet to be demonstrated successfully after more than a decade in development: The JTRS Ground Mobile Radio (GMR) program designed to run WNW was cancelled in 2011 after a series of failed tests, and the replacement program, the MNVR, a non-developmental item (NDI), has been under development for 2 years at the cost of ~$10 million per year. As of 2015,

MNVR has not yet demonstrated scalable mobile ad hoc network operation using WNW in an operational test. The Warfighter Information Network–Tactical (WIN-T), the Army's networking "backbone," has faced challenges in scalability, reliability, and soldier perception, despite years of investment in its dual waveform technology: the Highband Networking Waveform, and the Network Centric Waveform. WIN-T Increment 2 was determined to be not operationally effective by DOT&E in 2014, and the air tier (Increment 3), long the promised solution to a network fragmented by line-of-sight (LOS) limitations, was subsequently cancelled.

SRW is the cornerstone of the Army's lower tier tactical network. Over the next 10 years up to a quarter million radios, at a cost of several billion dollars (see Table 1-1 for procurement details and contract values for each of the SRW radios), are expected to run SRW. Ultimately, the value returned by this investment will ride on the performance of a waveform that has struggled to deliver any enhancement in communications during operational test and evaluation. Recent Network Integration Evaluations (NIE) have reported that radios operating SRW exhibited poor range compared to legacy systems, experienced excessive power consumption, and required a high level of network and spectrum management that may not be operationally feasible. In light of those observations, described in more detail in the sections below, we have performed a rigorous assessment of the SRW waveform in theory and application.

Table 1-1. Procurement Overview of SRW Tactical Radio Programs [1-7]

Program	Purchases to Date	Procurement Goal	Est. Contract Value	Est. Unit Cost
Rifleman Radio	21,379	193,276	$700-900 million	$5,600
HMS Manpack	(up to) 5,600	66,500	$6.5-9.0 billion	$72,000
SRW Appliqué	N/A	5,000	$988 million	$20,000
MNVR	232	2,500	TBD	TBD
AMF SALT	N/A	690	TBD	TBD
AMF SANR	N/A	7030	TBD	TBD
Total	~27,000	up to 275,000	$8 billion +	-

a. NIE 14.1 – CACTF Attack

One example that highlighted the ambiguity in SRW performance and soldier expectations was an incident at Network Integration Evaluation 14.1, which we refer to as the "CACTF Attack." This anecdote of poor SRW radio performance took place at the Combined Arms Collective Training Facility (CACTF) in White Sand Missiles Range (WSMR). A company commander described an exercise at the CACTF during which he struggled to communicate with his platoon leader who had entered a building only 80 meters away. Giving up on his radio, the commander resorted to running and yelling at the platoon leader. The platoon leader was unable to describe the problem he experienced beyond simply stating that his radio "was not working," leaving test

observers with a number of questions. Why were the commander and platoon leader unable to communicate despite being so close? Was it because the platoon leader entered the building? Was the platoon leader still connected to the network? Had network planning interfered with the routing options to the commander's radio? Given the uncertainty of what caused this incident, we were motivated to find out if some aspect of SRW might provide an explanation.

In addition to the instantaneous loss of connectivity upon reaching the urban-like environment, the soldiers reported that even in the convoy leading up to the CACTF, they could not connect or sense other SRW nodes beyond their own platoon, despite being within a few hundred yards of each other with direct, optical line of sight.

Upon closer look at NIE feedback, we found that the CACTF anecdote was only one example of what was to be more pointed and critical feedback from recent NIE assessments. In particular two operational assessment reports have highlighted a number of performance shortfalls that continue to be a problem for radios operating SRW:

b. NIE 14.1 – BMC Report on AN/PRC -117G OT

SRW performance during the Harris AN/PRC-117G OT at NIE 14.1 indicated that the waveform continued to suffer from a multitude of challenges. The Brigade Modernization Command (BMC) report highlighted three specific problems with SRW, rather than any specific radio, which warranted further investigation:

1. The "range of SRW radios hindered the dismounted force." The report cited that terrain and distances from gateway nodes isolated dismounted forces from higher/adjacent units' networks. This "severely limited voice communications, Position, Location Information (PLI), and messaging capabilities."
2. The network was "still too complex and difficult to manage." Changing network architecture to support unit task reorganization was "unsuitable for tactical operations."
3. The need for spectrum management has "increased significantly with the growth in the number of radios and the limited spectrum available."

c. NIE 14.2 – Maneuver Center of Excellence (MCoE) Memo on HMS FOT&E

Following HMS Follow-on Test and Evaluation (FOT&E) at NIE 14.2, General McMaster, MCoE commander, wrote a memo entitled "MCoE Operational Concerns with the AN/PRC 155 Joint Tactical Radio System (JTRS) Handheld, Manpack and Small Form Fit (HMS) Manpack Radio" [8] in which he detailed several issues with the Manpack radio running SRW:

1. There was "insufficient range in the dismounted configuration". An "86% decrease in range" was shown when compared to legacy SINCGARS dismounted radios.

2. The radios had an unacceptable battery life, achieving only 18% of the battery life compared to the existing dismounted Manpack radio. Excessive power consumption also led to dismounted configuration generating an unsafe amount of heat.

In our study, we have traced the vast majority of the issues reported, including lack of connectivity, throughput, excessive power consumption, limited spectrum availability, and increased network planning burdens to SRW. Some reflect actual shortcomings of the waveform, and others reflect a disparity between the waveform's original concept and its implementation on specific radio platforms and in specific network topologies. Given the importance of SRW to the present and future tactical network, we consider it imperative to understand the root causes of the disappointing performance of SRW radios in operational test. Our investigation into SRW's design and implementation also led us to question why some of SRW's most critical features – including its EW mode – have been largely absent from operational test. A section of this report is dedicated to a discussion about this important feature.

C. Analysis Overview

Our analysis of SRW is based primarily on a modeling and simulation approach described below, paired with our own observations from actual operational tests and careful review of waveform and radio design documentation [9, 10]. We used our observations from operational test to construct representative scenarios for simulation and configure SRW nodes according to the Army's implementation. We used the waveform documentation to study discrepancies between the Army's use of the SRW and the original concept for which the waveform was designed.

M&S is an essential tool when designing and testing networks, particularly when the network is set to operate in uncertain conditions and using unproven protocols. M&S can help predict environmental challenges, assess the sufficiency of test metrics and data collection, and observe the behavior of networking waveforms prior to test. In our case, we have found M&S especially useful for understanding how waveforms will behave in specific test topologies by simulating an envelope of network configurations that would be impractical to test in a live test event. In the following sections, we describe the modeling and simulation tools we chose for our analysis, and then outline our methodology for reconstructing specific NIE test observations in an M&S environment.

1. OPNET Modeler and Joint Communication Simulation Software

The network modeling tool that we used for our analysis is OPNET Modeler, which consists of a discrete-event simulator, specifically designed as a network model development tool. It is particularly suited to our study because it has the ability to incorporate ground movements, environmental/terrain effects on propagation, and time-varying traffic and to measure both global and individual link performance. OPNET Modeler is also the choice platform for the Defense Information Systems Agency's

(DISA) Joint Communication Simulation Software (JCSS) model libraries. JCSS is the Joint Chiefs of Staff's endorsed modeling and simulation tool for the warfighter, providing command, control, communications, and computers (C4) planners and analysts with a common modeling environment for planning and performance assessments. JCSS provides a library of military and commercial communication systems models (workstations, switches, terminals, transmission devices, and waveforms) that are designed to run on the OPNET core.

We utilize JCSS's SRW model, developed by Massachusetts Institute of Technology (MIT) Lincoln Laboratory, to represent SRW in the OPNET Discrete Event Simulation (DES) environment. The design and implementation of most features are based on specification documents [Waveform Design Specification (WDS) and Software Design Description (SDD)] and source code for SRW version 1.0.1.1 C. The model primarily comprises three layers that operate between the Transmission Control Protocol (TCP)/Internet Protocol (IP) layers and the physical layer: Subnet-Dependent Convergence Function (SNDCF) layer, Intranet layer, and Link layer, as shown in Figure 1-2.

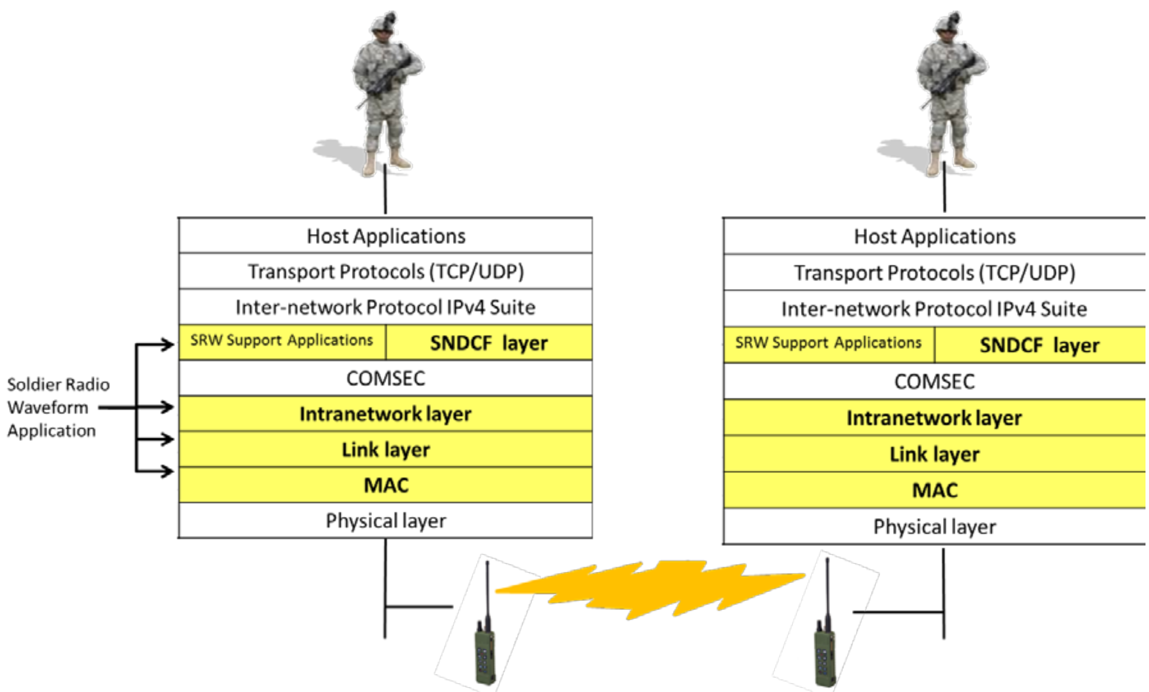

Figure 1-2. Protocol Stack View of SRW

SRW operates on the protocol layers highlighted in yellow. Core SRW operations reside on the Subnet-Dependent Convergence Function (SNDCF), Intranet, and Link layers.

2. Terrain Modeling

In OPNET, the physical layer is represented by a 14-stage "radio transceiver pipeline" that dynamically determines connectivity and propagation effects among nodes. Terrain effects can be incorporated into this model as additional path loss calculations, creating a high-fidelity presentation of the physical layer.

We imported terrain elevation data from the Digital Terrain Elevation Data (DTED) database into our simulations to understand the effect of terrain features on network performance. We chose to use the Terrain Integrated Rough Earth Model v4 (TIREM4) propagation model to calculate radio propagation path loss. TIREM3 is a widely employed model within the DoD, and TIREM4 is a more recent release that provides faster computation of path loss values. The model is the underlying propagation loss model for several M&S platforms other than OPNET and JCSS. These include Analytical Graphics, Inc. (AGI) Satellite Toolkit (STK), the Joint Network Management System (JNMS), and the Marine Corps' Systems Planning, Engineering, and Evaluation Device (SPEED) M&S tool.

TIREM4 calculates propagation loss over terrain elevations that are specified by a set of discrete points between the transmitting and receiving antenna. It can be used for radio frequencies in the range of 1 MHz to 40 GHz and takes into account factors describing the transmitting medium (humidity, surface refractivity) and antenna characteristics (polarization, height, frequency). The path loss calculation incorporates many effects including free-space spreading, reflection, diffraction, tropospheric scatter propagation, and surface wave propagation. It does not incorporate fading, ducting phenomena, ionospheric effects, or absorption due to foliage or rain. We note that while the latter (foliage and rain) are not relevant to the NIE cases examined in this report (where the climate is both treeless and dry), in the many forested and tropical climates of our world, radio attenuation will be further intensified by these features.

3. Network Topology Reconstruction Using TAPETS Data

We utilize The ATEC Player and Event Tracking System (TAPETS) to reconstruct soldier and vehicle trajectories in the simulation console. TAPETS tracks both vehicles and dismounted soldiers, providing second-by-second details of troop movements.

At NIE 14.1 each soldier and each vehicle was assigned a Positional Dismounted Soldier Unit (PDSU). Vehicle PDSUs were fixed on the vehicle; soldier PDSUs were portable and tracked their movements when dismounted. A unique PDSU number identified each soldier and vehicle in the TAPETS database. In a separate database, the PDSU number was used to identify a soldier's rank, platoon, squad, role, and vehicle number.

a. Tracking Soldier Movement

TAPETS data can be visualized using Common Data Link (CDL) 3D Visualization software, shown in Figure 1-3. Vehicle and soldier entities are displayed as blue rectangles (friendly forces) or red diamonds (opposing forces). Here we've highlighted (colored circles) the location of three soldiers we were interested in tracking: 1st Platoon Leader, 3rd Platoon Leader, and the Company Commander.

Figure 1-3. Vehicle and Soldier Positions Approaching the CACTF

TAPETS data, overlaid on satellite imagery, from a November 9th exercise. In this exercise a convoy of soldiers approaches the CACTF at WMSR.

Figure 1-4. Vehicle and Soldier Positions after Arriving at the CACTF

Soldiers dismount and several can be viewed entering the building shown in the top right.

In this exercise, TAPETS tracks the commander and platoon leaders as they travel in their vehicles up the road to begin an attack (Figure 1-3). Figure 1-4 shows a screenshot several minutes later when 3rd Platoon Leader and the Commander have joined 2nd Platoon Leader in the attack at the base. With high resolution satellite images of the urban environment, we can even determine which troops have entered a building.

b. Reconstructing a Scenario in M&S

GPS trajectory files for selected soldiers can be created from TAPETS data and imported in to OPNET. DTED data for the White Sands Missile Range/Fort Bliss region are also imported into the simulation, providing accurate terrain and elevation information.

We can then run SRW nodes along these trajectories to observe dynamic connectivity, latency, and terrain effects on radio performance. Even more importantly, this allows us to correlate the simulation output to specific key times from soldier/operator feedback. For instance, we investigated how terrain and choice of operating frequency affected communication between the company commander and a platoon leader traveling in a convoy on the way to the CACTF (Figure 1-5). In Figure 1-6 it's clear that by choosing to transmit with SRW over L-band frequencies, rather than SINCGARS over VHF frequencies, the operator incurs an additional 4 dB of attenuation over these distances.

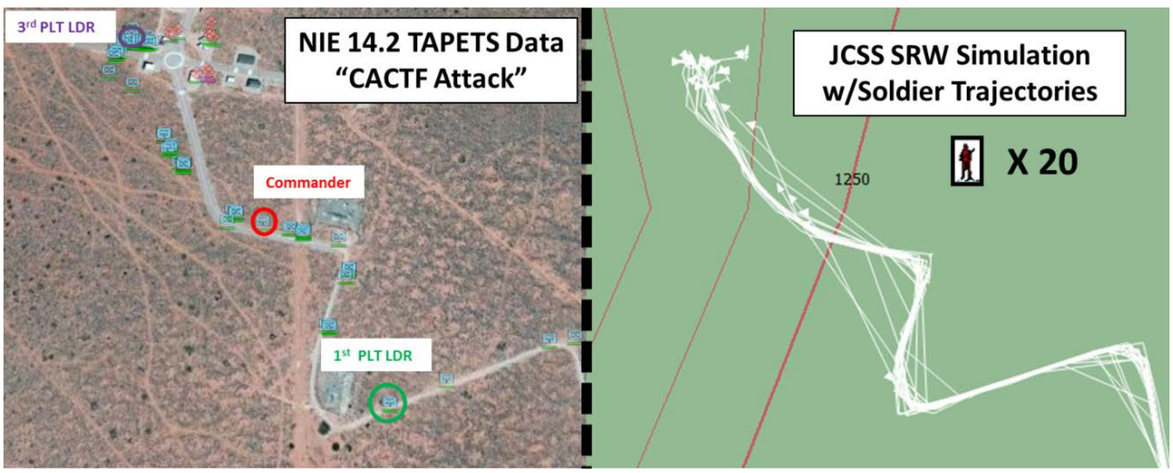

Figure 1-5. Side-by-side Comparison TAPETs Data and a Reconstructed Scenario in OPNET

The white lines in the right figure represent 20 vehicle and soldier tracks. Red lines are topographical data with elevation indicated in meters.

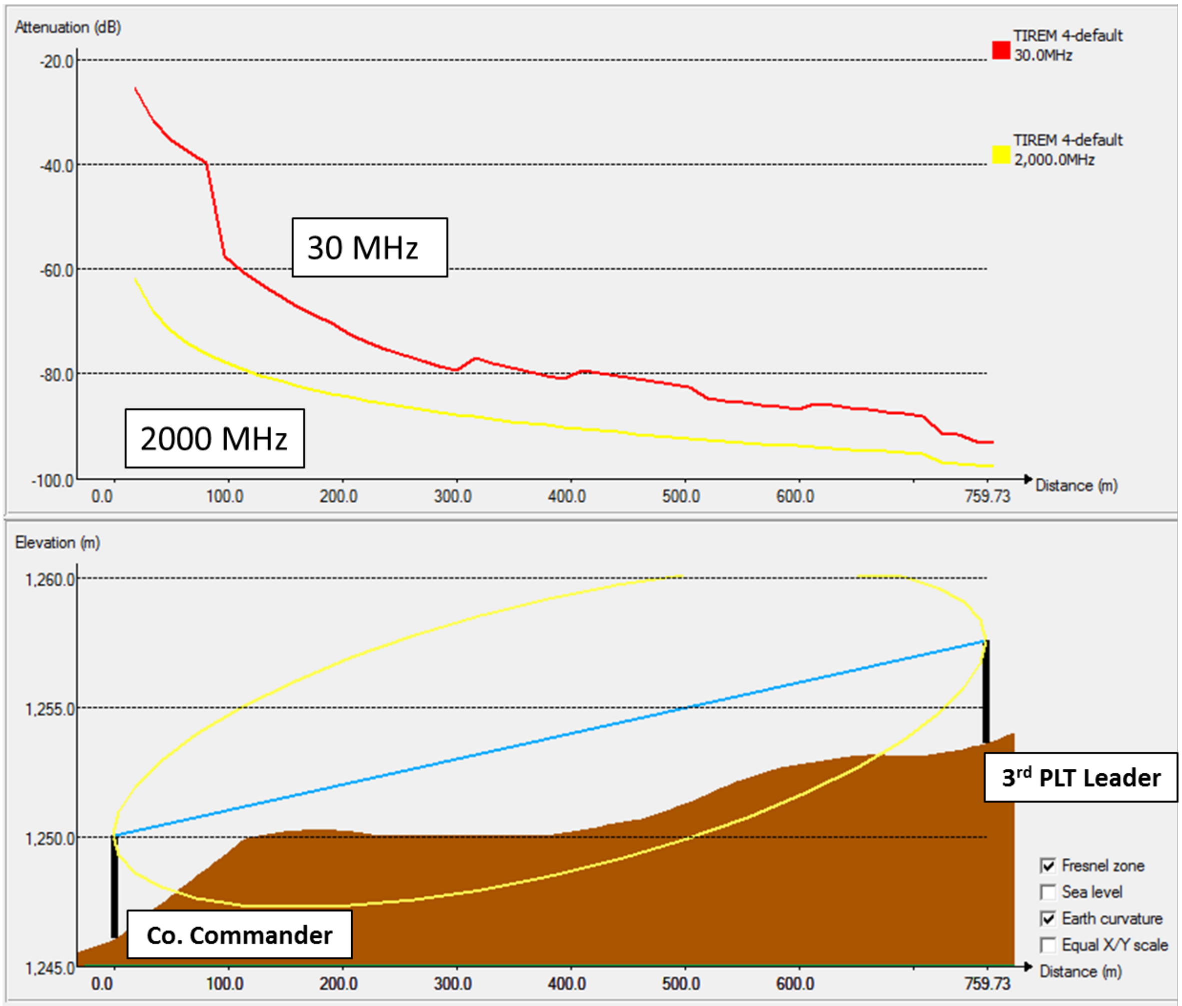

Figure 1-6. Terrain Profile and Signal Attenuation

Bottom: Cross section of the terrain elevation between the Company Commander and 3rd Platoon Leader at the positions shown in Figure 1-5. The blue line indicates line of sight, the yellow ellipse represents the first Fresnel Zone at an operating frequency of 2,000 MHz. Top: Signal attenuation plotted as a function of distance for two different frequencies (30 MHz – red; 2000 MHz – yellow). Attenuation was calculated using the TIREM4 propagation model.

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2. Analysis

A. SRW Network Design vs. Implementation

To ensure that our simulations are representative of actual operational test events, we resolved to incorporate actual soldier position information (TAPETS) collected during test, DTED of the actual terrain traversed by the soldiers during test, and network topologies used during operational test. In the process of researching the latter for SRW at NIE 14.1, we were surprised to learn just how much the network architecture used during test differs from that described in the waveform's original design documentation (SRW WDS [9]).

SRW was originally developed as a MANET waveform that would support an entire battalion of nodes (800+) on a single network. In reality, overhead traffic levels make fielding a working network of just 40 nodes a serious challenge. As a result, the SRW networks found at NIE testing are a striking departure from the original SRW vision. Rather than deploying a battalion-sized network, test planners have subdivided each company into a number of smaller SRW networks, each having fewer than 30 nodes. The motivation behind this architecture change is understandable – without scalability improvements to the waveform, this is the only way the desired number of nodes can be accommodated into the larger tactical network. While this approach may have provided some relief from the excessive amounts of overhead traffic experienced from the larger, fully connected network, the implications of these changes are extremely significant to various ways that the network functions.

1. SRW – As Designed

Fragmenting a single net has forced the waveform to operate on networks much smaller and more constrained than that for which it was originally designed. Connectivity under this revised architecture is limited, potentially crippling many of the routing advantages that make a MANET waveform like SRW so attractive. In addition to connectivity and routing implications, this revised architecture negatively affects two other areas of network performance. First, by breaking a single network into several smaller networks, it creates additional work for network planners who are already burdened by complex communication systems. Second, the problem of limited spectrum availability, in both operational test and on the battlefield, is further exacerbated by the additional bandwidth these many smaller networks require.

In this chapter we describe in greater detail how the configuration of SRW in operational test looks very different from its original design. We begin by describing the original SRW network architecture and how it enables the MANET capabilities of SRW.

We then discuss how the current network architecture differs and describe how these changes negatively affect connectivity, spectrum usage, and network planning.

a. Network Topology

SRW is intended to operate as an ad-hoc network, enabling communication through a self-configuring, infrastructure-less network of mobile nodes. It was originally envisioned that a single SRW network would support a battalion size force, composed of approximately 570 dismounted and 200 unmanned aerial communication nodes [10]. The waveform is designed to organize these nodes into the two-tier SRW network architecture depicted in Figure 2-1. The lower tier (1A) consists of multiple "islands" (these may be platoons and/or squads), typically composed of 20-40 nodes. The upper tier (1B) consists of tier 1A "island heads" (which provide a gateway between tier 1A and 1B), tier 1B-only participants (nodes that are at the company level or above), and gateway nodes to other external networks [WNW, Mobile User Objective System (MUOS), etc.]

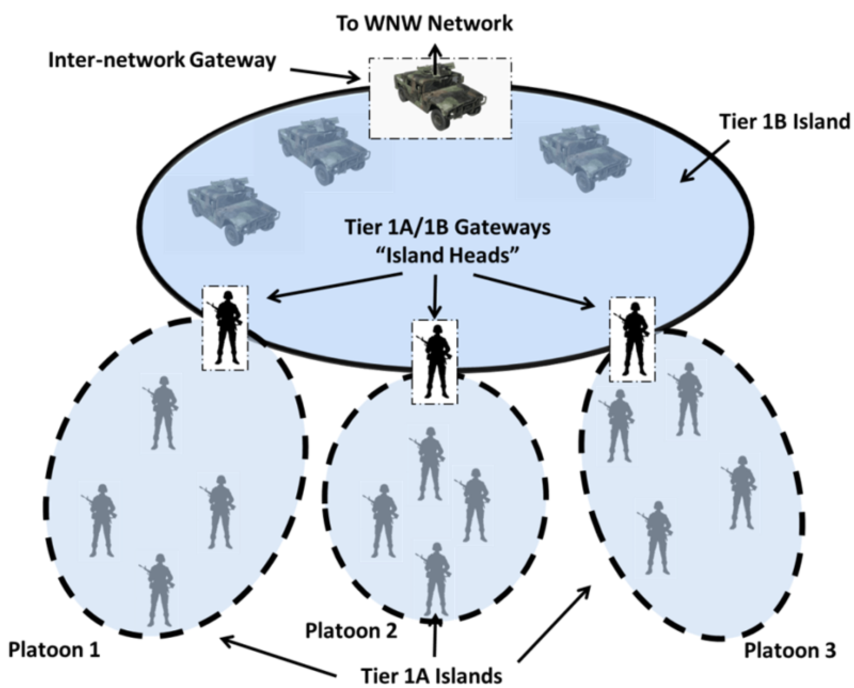

Figure 2-1. SRW Soldier System (SS) Network Topology

Tier 1A consists of multiple "islands" of nodes. "Island heads" provide a gateway to tier 1B, allowing data traffic to be routed among different islands. Dashed lines surrounding tier 1A islands indicate that island membership is fluid. All tier 1A islands operate on a single RF channel, all tier 1B nodes operate on a second, separate RF channel.

All tier 1A nodes operate on a single 1.2 MHz RF channel; tier 1B nodes operate on a second 1.2 MHz RF channel. Typically, dismounted tier 1A soldiers would carry a single channel radio such as the Rifleman Radio. Platoon or company commanders would carry, or ride in a vehicle with, a two-channel radio such as HMS Manpack or MNVR. This two-channel radio would have one channel assigned to each tier and act as communication gateway between the two.

b. Network Formation

In the SS domain, every SRW node is responsible for carrying out network formation and maintenance. These tasks include finding RF neighbors, evaluating link quality, establishing routing adjacencies, and deciding island memberships and roles. These tasks are distributed between the Link layer and Intranet layer of each node (see protocol stack in Figure 2-2).

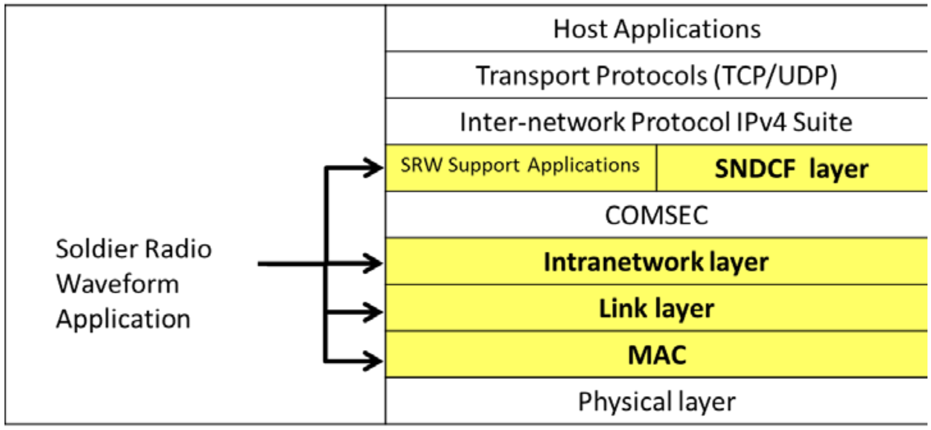

Figure 2-2. Protocol Stack View of SRW

SRW operates on the notional layers highlighted in yellow, collectively corresponding to the data-link and network layers in the traditional OSI model. Core SRW operations reside on the SNDCF, Intranet, and Link layers. The Link layer is responsible for neighbor discovery and evaluating link quality. Network formation and routing table generation occur at the Intranet layer. The SNDCF layer provides the interface between the Intranet layer and IP layer, facilitating the exchange of IP routing information.

The Link layer continuously runs a neighbor discovery process to find new RF neighbors and monitors link quality. It provides the Intranet layer with a "neighbor table" listing these RF neighbors and their respective link metric measurements. Based on this link quality information, the Intranet layer decides which nodes should join or leave an island, whether to merge or separate islands, and whether to promote or resign an island head. The Intranet layer also determines which node connections are "routing adjacencies," defined as bi-directional links exceeding a specific link quality threshold. Each node in an island may have multiple adjacencies within its island, and therefore islands tend to form mesh networks. Nodes are not allowed to form routing adjacencies with nodes from other islands.

c. Routing

SRW carries both routed (IP) and non-routed data. It is important to note that Combat Net Radio (CNR) voice is not routed; it is broadcast through repeated multi-cast relays. IP data, on the other hand, are routed utilizing a proactive routing protocol, akin to Open Shortest Path First (OSPF). Routing adjacency information is distributed among nodes through Link State Advertisements (LSAs). While tier 1A island members only receive LSAs from members in their own islands, island heads exchange their island's membership information with all tier 1B nodes. This allows the island head to create a

routing pathway from a node in its own island to a node in any island with membership in tier 1B. If a tier 1A node wishes to send data to a node within its own island, it directly forwards the data to that destination, using multiple RF hops if needed. If the destination node exists outside the source node's island, the data are forwarded to the island head who, in turn, forwards the packet onto the appropriate island.

SRW's routing architecture is designed to adjust to changes in link quality such that the connectivity of the network is never dependent on the quality of only a few specific links. With a large number of mobile nodes operating under one network, network topology can be reformed through island membership changes and routing adjacency updates, making it easier to mitigate the challenges of node mobility, terrain blockages, radio malfunction, etc. If, for instance, an island head moves behind a building and loses connection to its island, a new island head will be promoted, allowing that island to maintain connectivity to the upper tier. This "fluidity" of network formation and maintenance is one of the key advantages of a MANET waveform.

2. SRW – In Practice (Operational Test Network Topology)

Years of testing have shown that network overhead catastrophically limits network performance as network size scales upward. Though SRW was originally envisioned to work as a single network of 800+ nodes, there has been a failure to demonstrate a working network with more than 50 nodes. To be fair, this failure is not unique to SRW, as scaling beyond 50 nodes continues to be a challenge for all MANETs [save Defense Advanced Research Project Agency's (DARPA) Wireless Network After Next (WNAN) which succeeded in demonstrating a network of 103 nodes]. More troubling for SRW, however, is that this problem is unlikely to be mitigated with incremental improvements to today's MANETs. As a recent DARPA initiative implies [11], scaling to thousands of nodes is fundamentally challenged under existing IP-based protocols, and as such, a revolutionary new idea will be necessary. In the absence of scrapping the waveform, test planners are forced to work within these overhead constraints, which effectively limit "working" operational network size to 30 nodes. Our review of NIEs 14.1 and 14.2 network architectures indicate that the SRW networks deployed in these tests were constructed with this limit in mind.

a. NIE 14.1: Company Network Topology

At NIE 14.1, each company was distributed over several SRW networks. B-Co 1-35 for instance was separated in to four networks – one network for each of the three platoons in the company and one network containing the platoon leaders and company-level nodes. Each platoon was assigned an L-band frequency on which to operate its own SRW network, while the company-level net operated on a different UHF frequency. Platoon leaders were equipped with two-channel radios (or in some cases, two single-channel radios with a router in between) with one channel/radio operating in their platoon's net and the other in the company net.

Looking quickly at the NIE network architecture in Figure 2-3, one might wrongly assume that its configuration and behavior are nearly identical to the original SRW design (shown in Figure 2-1). Here we emphasize two important differences:

- The tier 1A/1B concept is no longer employed. "Tier 1A islands" in the original design are now individual SRW networks, each operating on a different channel frequency. The upper tier, "Tier 1B," is also a separate SRW network, operating on its own channel frequency.
- Network membership is preconfigured and fixed. Networks cannot merge or change member nodes. The neighbor discovery process operates on a frequency specific to each network, which means nodes from external networks will not be detected. As a result, nodes cannot join a new network if they become isolated from their original network.

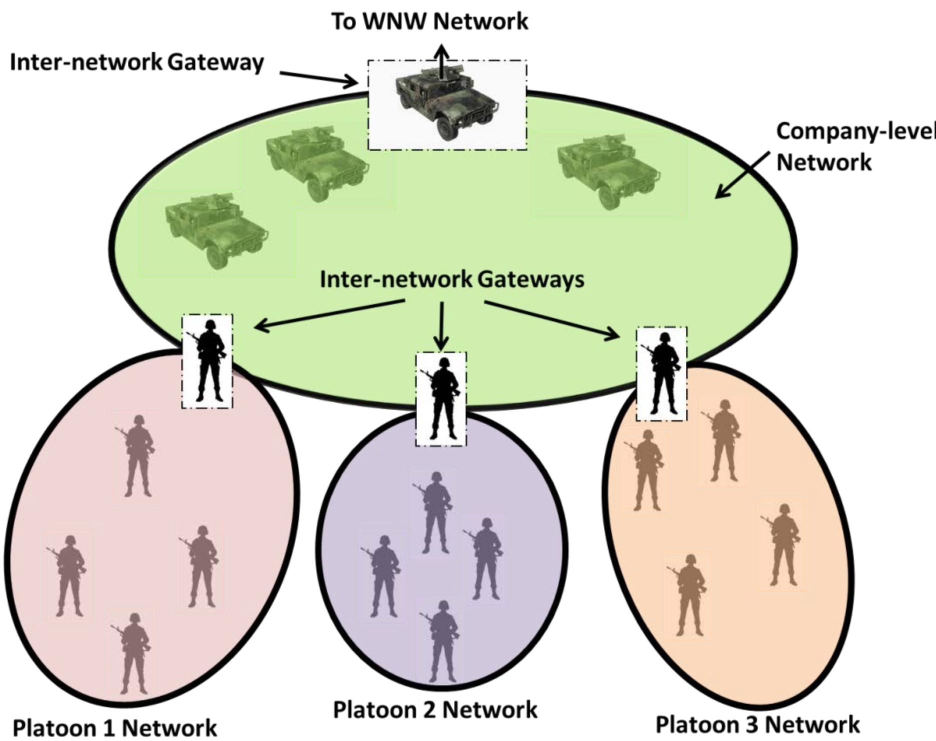

Figure 2-3. Schematic Representation of the Network Architecture for B-Co 1-35 at NIE 14.1

At NIE 14.1 B-Co was separated into four SRW networks (each shown as a different color): (1) 1st Platoon, (2) 2nd Platoon, (3) 3rd Platoon, and (4) Company-level nodes. Solid lines around each network indicate that network membership and size is fixed. Each network operates on a different radio frequency channel.

b. Scalability: Less isn't Always More

For a MANET such as SRW, a reduction in network size affects far more than network overhead. These architecture changes have critical ramifications on connectivity, spectrum use, and network management.

Connectivity – First and foremost, reducing network size diminishes connectivity by limiting the number of potential pathways from source to destination. In a sparser network, nodes may find that they have fewer nearest neighbors and that the nearest neighbors they do have are farther away. Decreasing the number of nodes limits routing options, making it much more difficult for SRW's routing algorithm to overcome poor link quality.

Breaking a large SRW network into several smaller ones is particularly counterproductive for CNR calls, which utilize a point-to-multipoint broadcast method to transmit (see Section 2.C, SRW Combat Net Radio Voice, for a more detailed description). While CNR calls may be relayed directly across tier 1A islands, they cannot propagate across different SRW networks. As a result, under the NIE network architecture, a node in 1st Platoon would not be able to relay through a node in 2nd Platoon, even if that node offered the best (or only) pathway to the destination node.

Pre-configuring smaller networks further inhibits connectivity by handcuffing SRW's "ad-hoc" capabilities. The SRW is designed to compensate for link quality deficits with topology manipulations that improve network performance – for instance breaking apart (or merging) islands, allowing new nodes to join an island, or replacing an island head with a more advantaged node. In the NIE implementation however, such adaptations are almost entirely impossible because island size and island membership are fixed. For example, consider the NIE architecture in Figure 2-3 and the case where a node in 1st Platoon finds itself isolated from its fellow 1st Platoon nodes. The isolated node in 1st Platoon could join a neighboring island (2nd or 3rd Platoon) under the original network implementation, but in the NIE architecture it would remain isolated until it could finally regain contact with 1st Platoon. Although nodes in 2nd and 3rd Platoons may be in RF range of the isolated node, they would be unaware of its distress because they operate in different networks on different frequencies. Without any means to reorganize the network topology on the fly, the reliance on any one node or link increases significantly in the NIE test architecture.

Effect on Network Management – A byproduct of NIE implementation is that network planners are now responsible for organizing and managing a greater number of SRW networks. Instead of a single SRW network for each company, there are now four (one for each platoon and one for company-level nodes). By manually pre-configuring these small networks, the value of SRW's "self-forming" capabilities is diminished, shifting additional network management work from the waveform to network planners. This increases the burden on soldiers and undoubtedly contributes to a network that BMC has described as "still too complex and difficult to manage."

Effect on Spectrum Allocation – A final complication of the NIE network architecture is that additional bandwidth is needed to support its operation. Whereas a single company network only requires two 1.2 MHz RF channels (one for tier 1A and one for tier 1B), the revised architecture needs double that bandwidth, requiring four 1.2 MHz RF channels (one for each of the three platoons and one for the company-level network).

This increase in bandwidth should give cause for concern given that the RF spectrum is an extremely limited resource both in operational testing and on the battlefield. The BMC test report from NIE 14.1 noted that the need for spectrum management has "increased significantly with the growth in the number of radios and the limited spectrum available." We would amend this statement, by counting "SRW network architecture changes" among the other drivers limiting spectrum availability.

3. Conclusions

A current constraint of all MANETs is that they are generally unable to scale beyond 50 nodes without network overhead crippling performance. SRW is no exception. Several years of testing have achieved an operationally effective network of approximately 30 nodes – a tiny fraction of the 800-node network that SRW was originally intended to form. These overhead constraints have forced major architecture changes that handcuff SRW's capabilities, limiting important MANET advantages that warranted the development of a complicated and expensive waveform in the first place. Furthermore, these changes have exacerbated complications in spectrum availability and network management.

B. Network Traffic: Overhead vs. Demand

Network overhead issues continue to be a fundamental challenge for all mobile ad-hoc networks. In the case of SRW, overhead traffic has significantly exceeded original expectations, placing unwelcomed limitations on network size and throughput. Though high overhead is often blamed for poor network performance (usually with good reason), we are unfamiliar with any M&S efforts that have identified SRW-specific waveform, network, and environment characteristics that drive overhead levels. If we hope to learn the true extent of SRW's overhead issues and develop effective approaches for mitigation, understanding the root cause (or causes) will be necessary. To address this need, we ran a set of simulations that evaluated the effect of four key factors on network overhead: number of nodes, node density, mobility, and terrain. The first factor, the number of nodes in the network, has long been recognized as a driver of overhead and is a rather obvious observation from both laboratory and operational testing. A more difficult challenge, however, is isolating the effect of the remaining three factors on overhead, and this is something that is most easily done in simulation. In this section we focus on the effects of terrain, mobility, and node density in small networks approaching the size limits currently constraining SRW operation.

Our simulations, which modeled a SRW network over WSMR terrain, found that terrain interference and low node density are particularly strong drivers of network overhead. These factors, even at smaller network sizes (20 nodes) can create overhead traffic levels that equal or exceed network data traffic demands. A detailed analysis of Link layer traffic suggests that both terrain interference and low node density drive greater overhead messaging through their degradation of link quality. We observed that

under conditions of weak connectivity, SRW's proactive routing protocol creates excessive overhead as it struggles to monitor the quality of links and establish adjacencies with its neighbors. Even over the mild terrain of WSMR, attenuation and multipath interference is great enough to degrade signal strength and influence overhead message traffic. An equally important observation was that reduced node density can greatly exacerbate link-quality-driven overhead. Reducing node density increases the separation between nearest neighbors and decreases the number of routing pathways and, by so doing, makes terrain-degraded connectivity ever more tenuous. If the smaller networks now employed in operational testing result in reduced node density, our simulations suggest that this fragmentation could actually be counterproductive to overhead management.

In this section we begin with a brief overview of SRW's algorithms for network formation and routing, emphasizing tradeoffs between proactive and reactive protocols. In the subsections following, we describe our simulation configurations, characterize network connectivity, and then examine what factors control network overhead and convergence time. We conclude with a discussion of how the tactical waveform community is planning to address SRW's overhead challenges and what other, potentially more painful, changes may be necessary to improve the viability of this waveform.

1. SRW Network Formation and Routing

SRW utilizes a *proactive* protocol to construct network topology and manage the changing connectivity of mobile nodes. Its protocol is "table-driven," meaning that each node maintains an updated table of the routing pathways to all other nodes. This route information is proactively created for all destinations, regardless of whether traffic actually needs to be sent at that time. However, to keep these routing tables current, periodic control and link-state messages must be frequently sent throughout the network, potentially leading to high overhead. This proactive routing is in contrast to a *reactive* or "on-demand" style protocol. Rather than taking the initiative to find routes to all destinations, a reactive protocol waits until prompted to send traffic to a specific destination before attempting to discover a route. Reactive protocols significantly reduce overhead because they minimize periodic control messages that would be needed to update routing information. The downside is high latency due to the time spent searching for a route, particularly in networks with dramatic topology changes.

SRW's network formation and routing processes rely on proactive messaging, allowing route discovery prior to a message request, at the cost of high overhead. Proactive messaging at the Link layer provides link quality information and neighbor discovery, while proactive messaging at the Intranet layer distributes routing information and network topology updates.

a. Link Layer – Neighbor Discovery and Link Quality Evaluation

Each SRW node's Link layer is responsible for finding neighbors within RF range and determining the quality of the link to those nodes. To accomplish these tasks, the Neighbor Discovery (ND) function monitors the status of links by periodically broadcasting messages to all radios within RF range. One proactive message type essential to this process is the *Packet Radio Organizational Packet* (PROP). These messages are used to verify the ability of local nodes to establish and maintain bi-directional links, and they contain important link quality information [such as the signal-to-noise ratio (SNR) at the receiver]. Through these messages, the Link layer is able to continuously measure the link quality of RF neighbors, creating neighbor information tables that the Intranet layer subsequently uses to optimize routing and network topology.

b. Intranet Layer – Network Formation and Routing

Based on the link quality information provided by the Link layer tables, the Intranet layer determines which nodes meet the criteria to be "routing adjacencies" and therefore can route message traffic. Each node generates and proactively broadcasts their routing and topology information to other nodes through *Link State Advertisement* (LSA) messages. Using this information, each node calculates the most cost-efficient routes given their neighbors' link strength and status. Route calculation follows a routing protocol similar to the OSPF protocol.

2. Simulation Configuration

In the sections to follow we analyze a total of 24 scenarios to determine the effect of four factors on SRW network overhead and convergence. Table 2-1 shows the parameter space for each of the factors.

Table 2-1. Simulation Factors and Configurations

Factors	Configurations
Number of Nodes	5
	10
	20
Node Density (Nearest Neighbor Separation)	60 m ("Dense")
	500 m ("Sparse")
Mobility	Static
	Mobile
Terrain Propagation Model	No Terrain Modeling
	TIREM4

a. Number of Nodes

We chose 3 network sizes to investigate: 5, 10, and 20. These sizes are only a tiny fraction of the theoretical maximum size of an SRW network (800+ nodes) and less than the 30-node limit that has more recently been recognized as a threshold for acceptable network performance.

b. Nearest Neighbor Separation

We defined two node spacings. The first is a "dense" spacing, with nearest neighbor separations of approximately 60 meters and network areas ranging from 0.02 to 0.06 km^2 (depending on the number of nodes), depicted in Figure 2-4. As discussed in the next section, in this configuration, every node has a strong link to each of its neighbors. The second configuration is a "sparse" spacing, with nearest neighbor separations of approximately 500 meters and network areas ranging from 0.6 to 4 km^2. In this configuration, nodes use their nearest neighbors as intermediate hops to more distant neighbors.

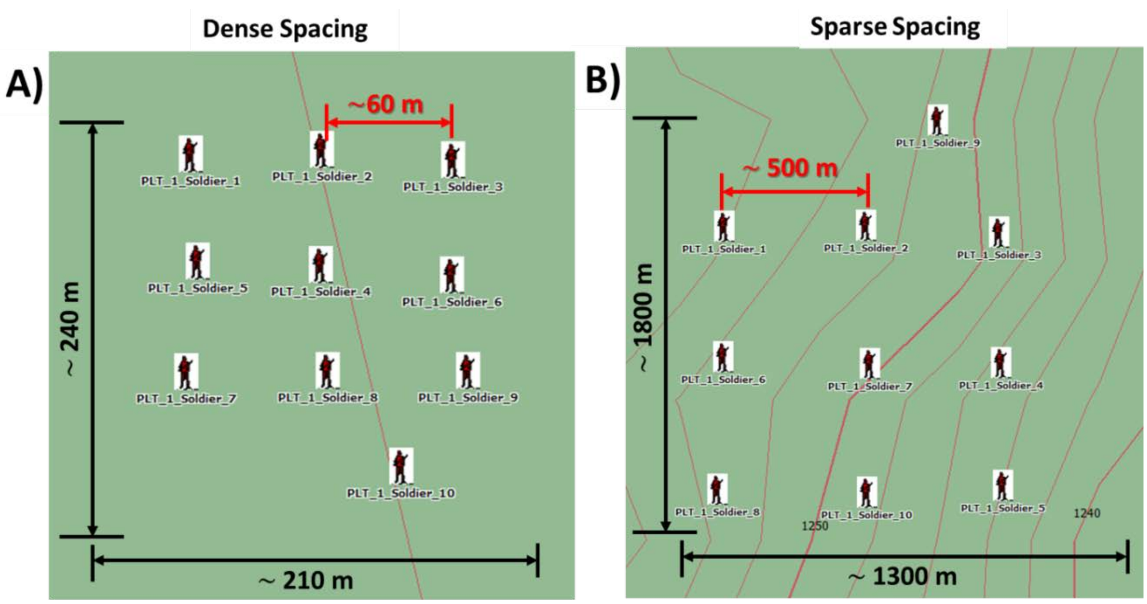

Figure 2-4. Node Spacings used in Simulations

A: "Dense" configurations have a node spacing of approximately 60 meters.

B: "Sparse" configurations have a node spacing of approximately 500 meters.

c. Mobility

Mobile scenarios include a fraction of mobile nodes (2-5 nodes) that follow pre-defined trajectories. Figure 2-5 shows the network configuration for a 10-node "sparse" scenario. (Note: TAPETS trajectories were not used in these simulations. This was a necessary simplification to allow a direct comparison between the different scenarios.) In all mobile scenarios, mobile nodes remain at their initial positions for the first 20 minutes of the simulation. After this initial convergence period, the mobile nodes follow their trajectories for the remaining 40 minutes (total simulation time is 60 minutes).

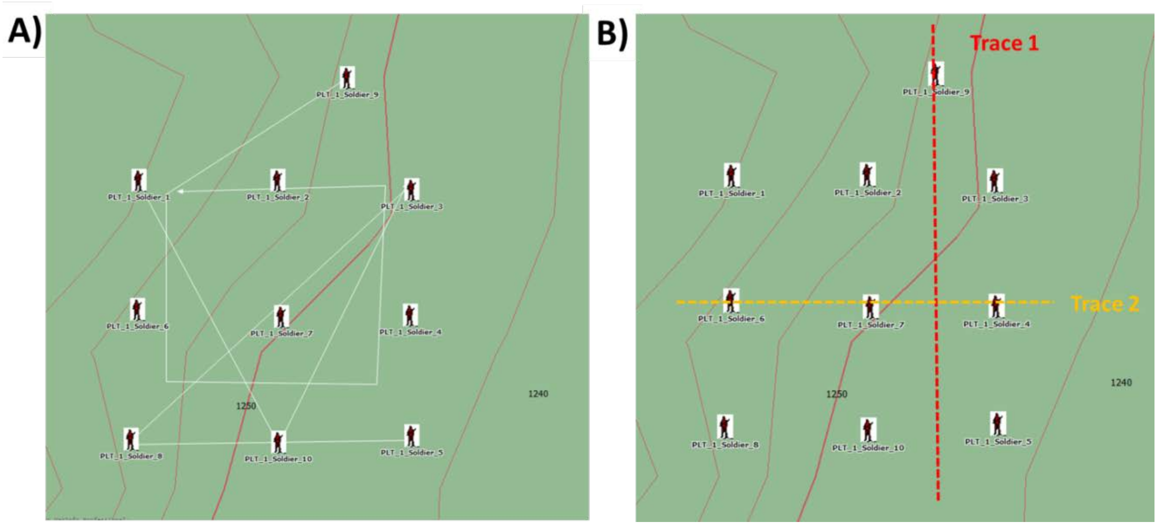

Figure 2-5. (A) 10-node "Sparse" Scenario with Three Mobile nodes; (B) 10-node "Sparse" Scenario Overlaid with Location of Topology Traces

White lines indicate trajectories of mobile nodes. In this example, three nodes are mobile: "PLT_1 Soldier 1," "PLT_1 Soldier 3," and "PLT_1 Soldier 9." All nodes are stationary for the first 20 minutes of simulation, after which mobile nodes follow their trajectories for the remaining 40 minutes of the simulation.

d. Terrain Characteristics

All networks were positioned near the location of the "CACTF attack" at WSMR, a region representative of the typical NIE test environment. This environment is characterized by micro-terrain (small mounds) in what is essentially a treeless desert valley. Figure 2-6 provides two terrain profile traces of this region using DTED elevation data. These traces confirm the benign nature of the environment – gently sloping terrain with only minor elevation changes over the areas of interest.

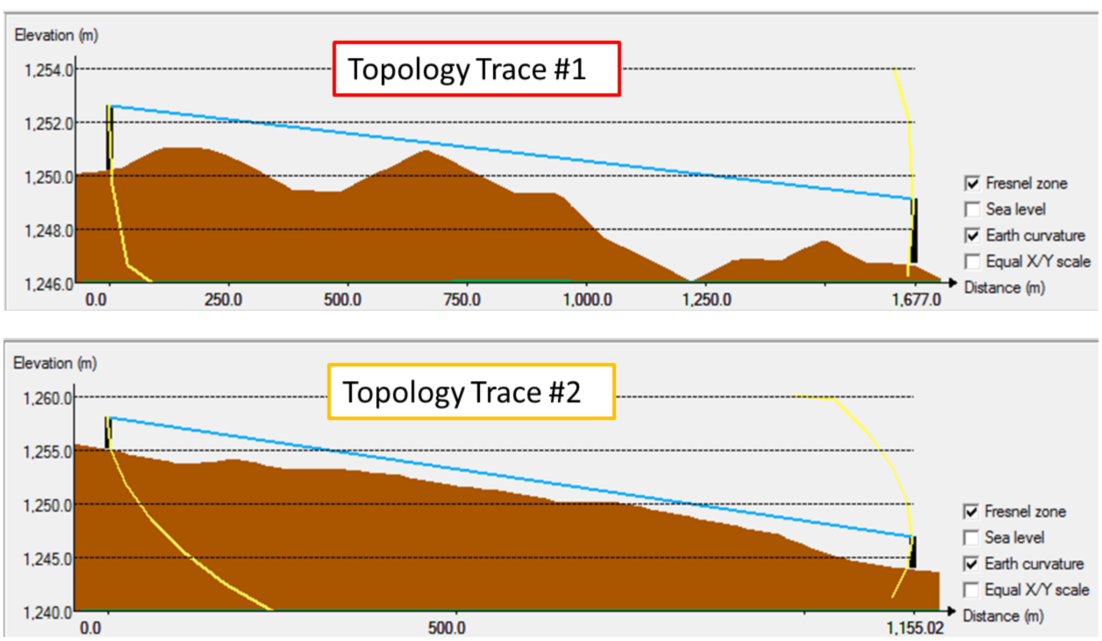

Figure 2-6. Terrain Profile of Topology Traces Shown in Figure 2-5B

Terrain profiles from the CACTF region of WSMR. Yellow ellipses represent the first Fresnel zone; blue lines represent line-of-sight. Antenna height is set to 3 meters.

e. Radio/Network Settings

All nodes were configured as single-channel radios with an antenna height three meters above the ground. All nodes were assigned a unique IP address on a single SRW subnet. No restrictions were placed on island or tier (1A/1B) memberships. Therefore, the network was expected to form and heal like a true MANET, unlike the constrained and predetermined topology used at NIE 14.1.

f. Simulation Execution

Each scenario was run a total of 10 times, with a different random number seed for each run. In the plotted results that follow, error bars represent ± the standard error calculated from these 10 runs.

3. Network Connectivity

Link quality paces the performance of any network, forming the foundation for our understanding and interpretation of simulation outputs. Therefore, we begin our analysis with a discussion of network connectivity.

It is difficult to gauge network connectivity from any single output metric, but qualitative descriptions of network connectivity can be garnered from two simple Link and Intranet layer statistics. The first is “neighbor count,” a Link layer statistic that describes the average number of RF neighbors detected by the nodes. Of the link statistics that can be collected by the JCSS modeling suite, the “neighbor count” statistic has the lowest threshold for defining a link, only requiring enough link capacity to receive small neighbor discovery messages. Therefore this statistic should be interpreted as a minimum requirement for connectivity. A second, more selective statistic is the “reachable node count.” This is an Intranet-level statistic that describes the ability of a node to reach other nodes, either directly or through one or more intermediate node hops. This statistic requires sufficient link strength to support Intranet layer message traffic and the establishment of an Intranet layer routing table.

Figure 2-7 shows the reachable node statistics for 5- and 20-node scenarios without terrain modeling. We see that in these scenarios (dense/sparse/mobile/static permutations) all nodes are reachable (4 and 19 nodes respectively for the 5 and 20 node scenarios). Similarly, the 10-node scenarios without terrain modeling (data not shown) have a saturated reachable node count.

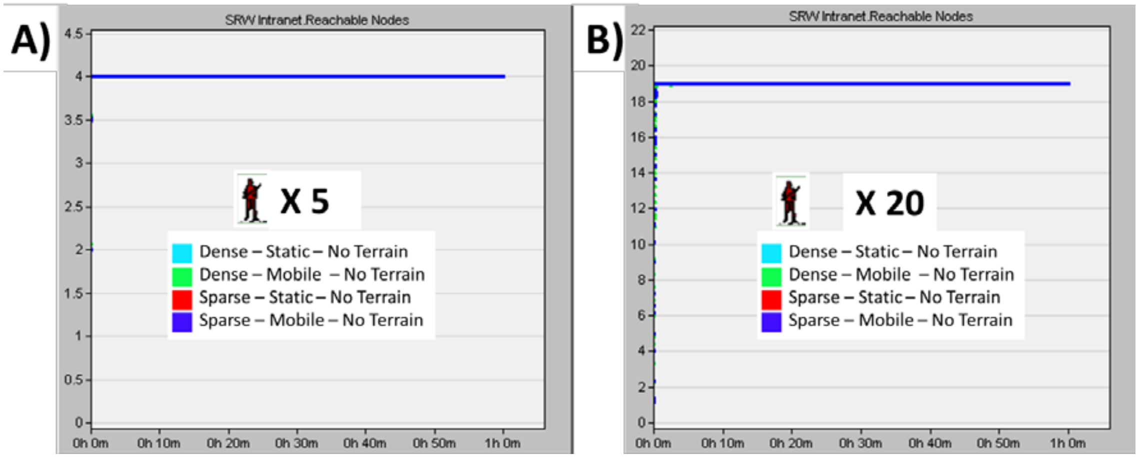

Figure 2-7. Reachable Node Count for 5- and 20-Node Scenarios without Terrain Modeling

For the 5-node scenario (plot A), a reachable node count of 4 indicates that each node has intranet connectivity to its 4 neighbors. Similarly for the 20-node scenario (plot B), a reachable node count of 19 indicates that each node has Intranet connectivity to its 19 neighbors. These stable and saturated reachable node counts indicate that these networks have strong link quality and connectivity.

Things become much more interesting when we look at the scenarios *with* terrain modeling. Figure 2-8 shows the neighbor and reachable node-count evolution for these scenarios. First we note that, except for a few brief instances when the nodes are mobile in sparse scenarios, the neighbor node count is saturated throughout the simulation, indicating that, at least in the view of SRW's neighbor discovery process, there is complete "connectivity" at the Link layer.

The reachable node statistics however, tell a different story about the quality of these links. In the 10 and 20 node "sparse" scenarios (Figure 2-8 D and F), the reachable node count is fluctuating below 9 and 19 nodes, respectively, signifying that some nodes are having a difficult time transmitting messages at the Intranet layer. In the 20-node scenarios (Figure 2-8 F), we see that reachable node count actually improves over time in the sparse-mobile scenario. Not surprisingly this improvement occurs just after 20 minutes, the time at which the mobile nodes begin to follow their trajectories, and presumably move into more favorable locations.

The neighbor and reachable node counts point to several connectivity trends. As expected, once terrain modeling is incorporated, link quality degrades. Even within the benign terrain of WSMR where line of sight often exists, terrain and other blockages can degrade the signal, due to multipath Fresnel zone interference. Although neighbors may be detected, the degraded signal-to-noise ratios limit channel capacity and link throughput, as described by the Shannon-Hartley theorem. The theoretical backing for these subjects is expanded upon in Section 3.A. We have found empirically through M&S that decreasing node density further exacerbates the problems of network connectivity. A sparsely populated network has fewer routing pathways making it more difficult to overcome terrain-induced link degradation.

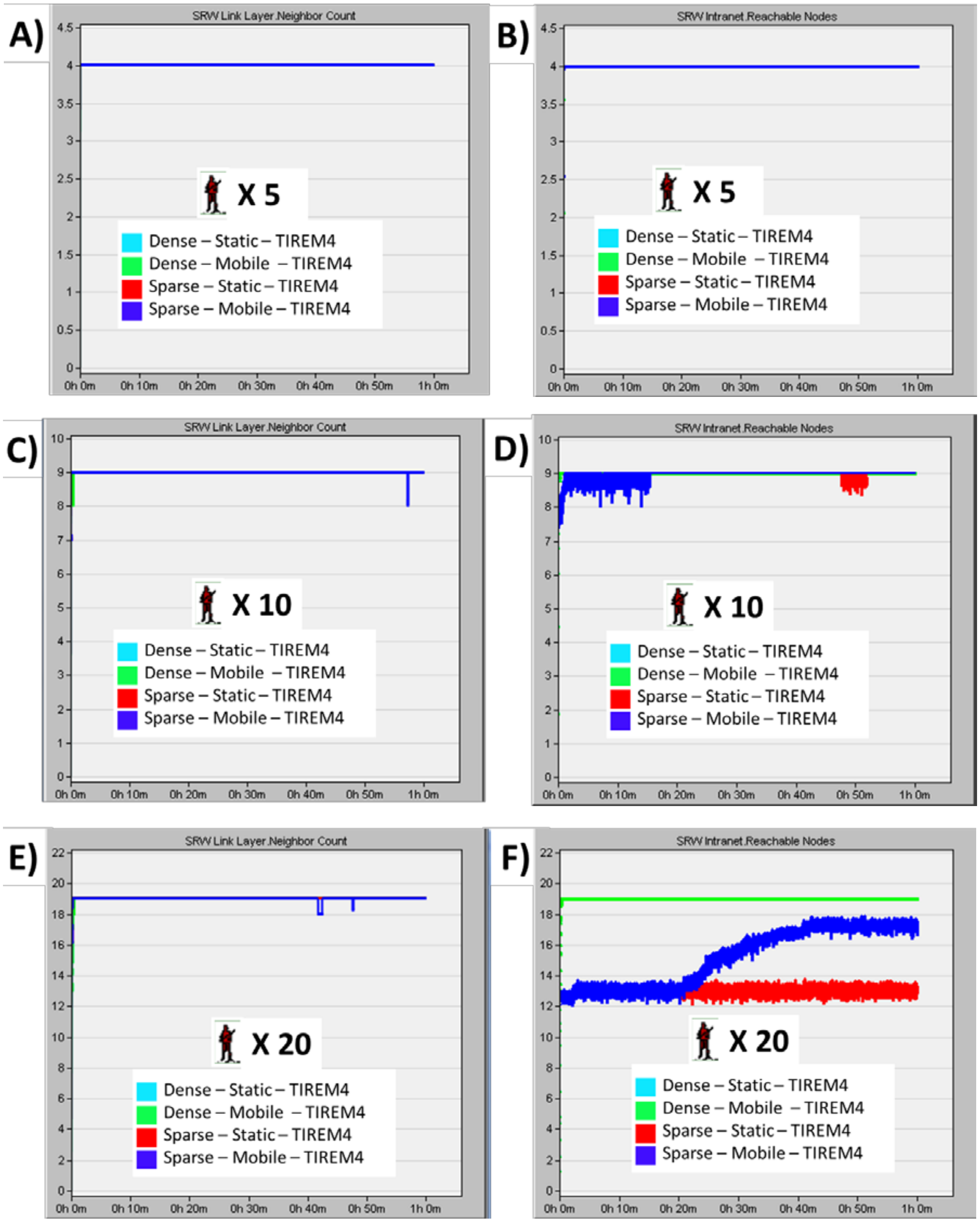

Figure 2-8. Neighbor Count (A, C, E) and Reachable Node Count (B, D, F) for Scenarios with Terrain Modeling

In the 10- and 20-node "sparse" scenarios simulated with terrain (plots C-F), each node has "discovered" all possible neighbors, as indicated by saturated neighbor node counts in plots C and E. Intranet connectivity, however, is not complete, as indicated by fluctuating and unsaturated reachable node counts in plots D and F. This behavior suggests that these networks suffer from poor link quality.

4. Network Overhead

How do our four factors – number of nodes, node density, mobility, and terrain – affect network overhead? Figure 2-9 shows overhead traffic, specifically the aggregate received overhead traffic, as a function of these four factors (we have also confirmed that sent traffic behaves in similar manner). We see that network overhead increases from approximately 20 kbps for the 5-node scenario to more than 40 kbps for the 10-node scenarios and to more than 180 kbps for the 20-node scenarios. Not surprisingly, the highest overhead rates are observed in scenarios with terrain effects and mobility.

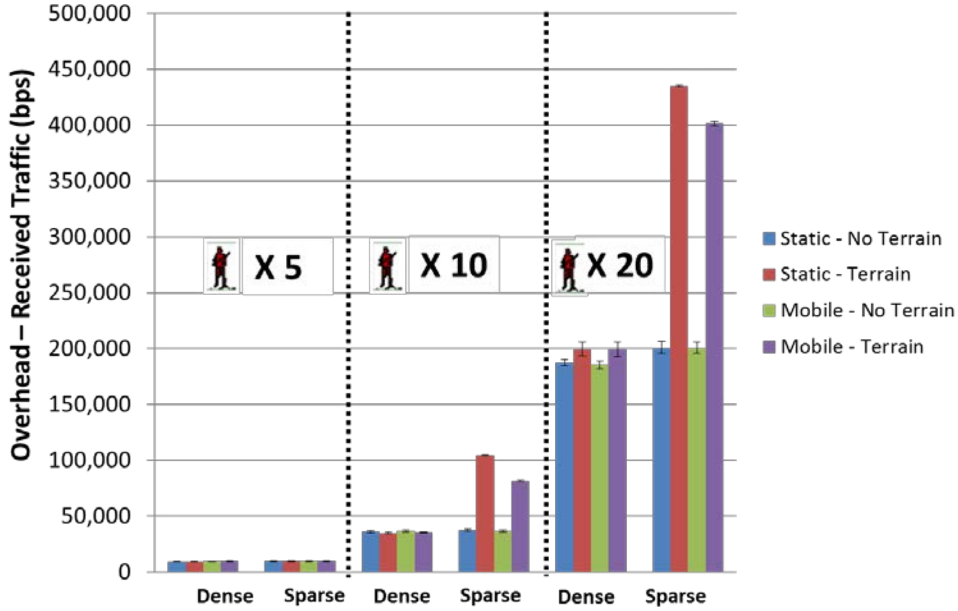

Figure 2-9. Aggregate Overhead Traffic

This plot shows aggregate received overhead traffic. Overhead traffic consists of network management messaging at the Link, Intranet, and SNDCF layers. Two dominate trends appear in this plot: (1) increasing overhead traffic with increasing network size; and (2) significant increases in overhead traffic under conditions of poor link connectivity. The latter occurs for scenarios with sparse node dense and terrain modeling

A less intuitive observation is that the highest overhead scenarios are also those with sparsely populated networks. Node density appears to be a particularly important factor, a fact that is most clearly evident in the 10- and 20-node scenarios. In these sparse networks, network overhead is more than double that of the dense network. These results are even more troubling when we compare these overhead rates to the expected Information Exchange Requirement (IER) loadings taken directly from the SRW System Performance Specification v.1.9.3 (see Appendix D). In Figure 2-10, we plot the operational message loading, estimated from the message requirements, against the overhead loadings generated in simulation. In the 10- and 20-node scenarios, where link and network management traffic is equal to or greater than message traffic, it is doubtful that the available throughput will be able to support all traffic, likely leading to degraded network performance.

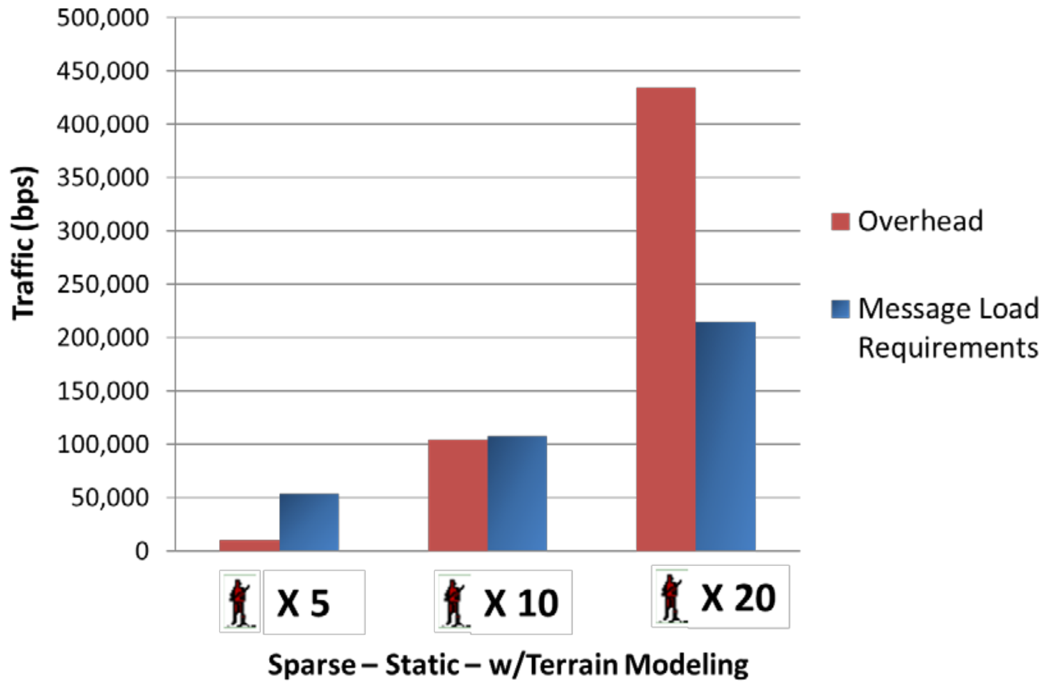

Figure 2-10. Comparison of Overhead Traffic for "Sparse – Static – Terrain" Scenarios with SRW SPS Message Load Requirements

Together terrain interference and low node density drive network overhead traffic to levels that equal or even significantly exceed the network's expected data traffic loads.

To further understand the origins of this overhead behavior, we chose to break the overhead activity down in greater detail. Figure 2-11 separates overhead traffic in four scenarios (20-node networks modeled with terrain effects) into overhead activity at the Link, Intranet, and SNDCF layers. We see that in the sparse scenarios, the increase in overhead activity is driven almost exclusively by an increase in Link layer activity. Going a step further, we can break down this Link layer activity into specific message traffic as shown in Figure 2-12. It's evident that one message type, PROP (Packet Radio Organizational Packet), is driving the increase in overhead activity. These messages contain link metric information and are used by the waveform to verify the quality of links before establishing a bi-directional data link.

The increase in PROP message traffic is not unexpected, given SRW's proactive routing protocol. Proactive routing regularly floods the network with link states and maintains local routing tables at each node. While proactive routing is optimized to minimize latency by regularly refreshing the routing table, this comes at the expense of additional overhead. When RF transmissions from a node have been "detected" (akin to the neighbor statistic we collected earlier), local nodes attempt to exchange PROP messages to establish communications link parameters and verify that a bi-directional data link can be maintained. PROP messages are then regularly broadcast to reevaluate the link quality until a connection can be made. When nodes have degraded links with their neighbors, such as happens in the "sparse-terrain" scenarios, this proactive flooding can cause a significant run-up in overhead.

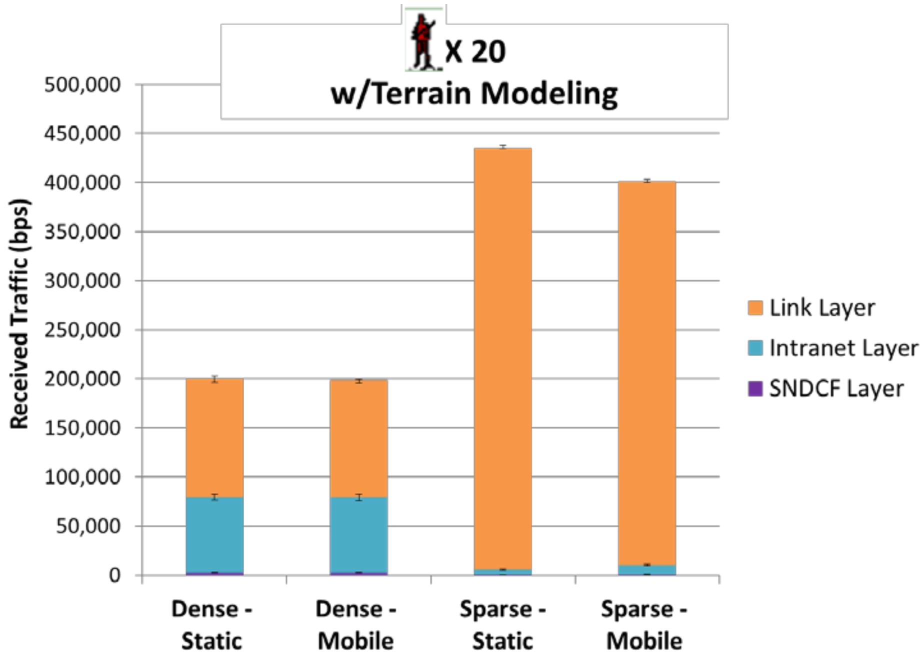

Figure 2-11. Overhead Traffic Broken Down by Link, Intranet, SNDCF Layer

Four 20-node scenarios are shown: (1) “dense – static – terrain,” (2) “dense – mobile – terrain,” (3) “sparse – static – terrain,” (4) “sparse – mobile – terrain.”

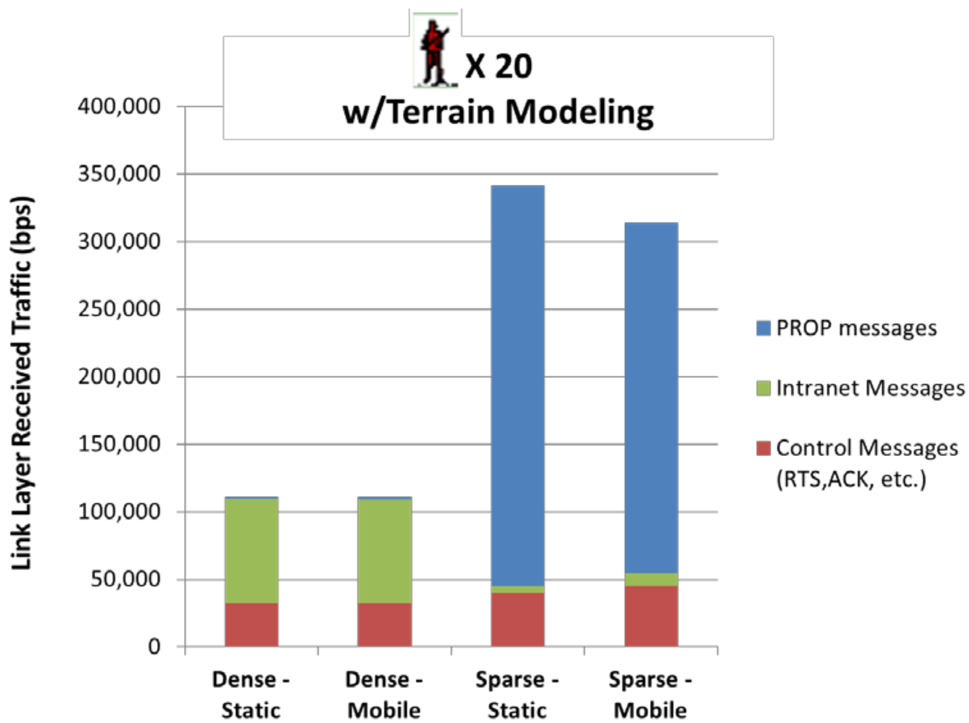

Figure 2-12. Link Layer Activity by Message Type

Link layer activity broken down by message type for the four 20-node scenarios plotted in Figure 2-11. In scenarios with low-node density (sparse), PROP messages traffic increases dramatically due to the weak links present in the network.

5. Network Convergence Times

In addition to these increases in overhead, poor link quality in sparse network configurations can negatively affect a network's convergence time. In Figure 2-13, we plot convergence time for the 5-, 10-, and 20-node static network scenarios. We define convergence time as the IP layer convergence time, or more specifically, the elapsed time from the start of the simulation to the time of the last change to IP forwarding/routing table. We caution the reader not to assign too much significance to the specific convergence times, but rather suggest that one simply assess the general trends. Convergence times are not only highly dependent on specific details of network configuration and terrain, but also are heavily influenced by the random network behavior of SRW (random number seed). Cognizant of this fact, we present in Figure 2-13 average convergence times from a total of 10 runs (each run uses a different random number seed), and we point out that there are large error bars (and standard deviations) in the 10- and 20-node static-terrain scenarios.

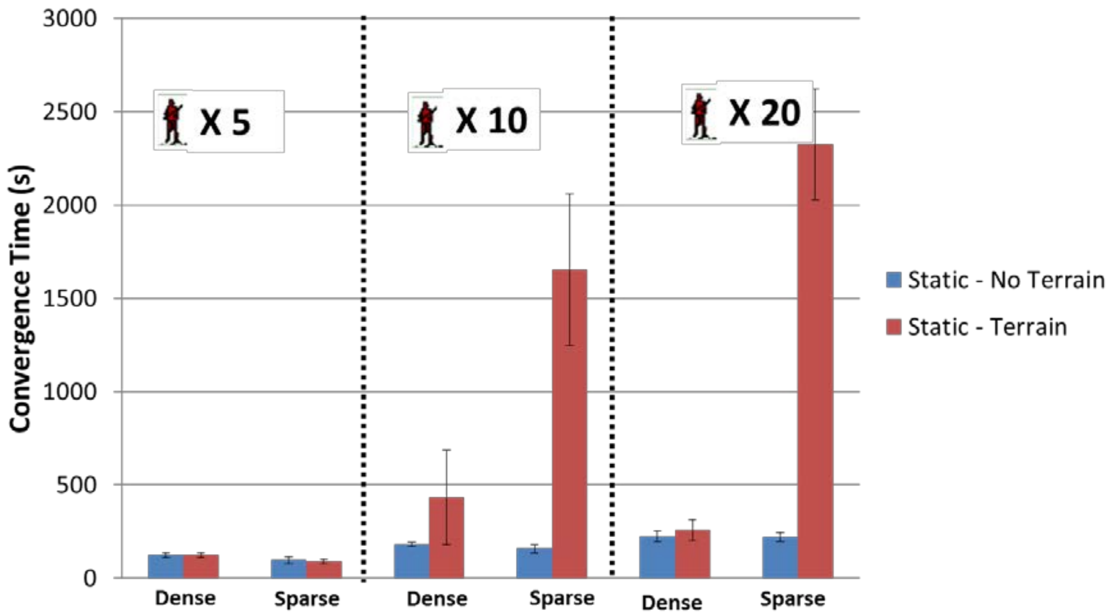

Figure 2-13. Convergence Times

The trends in Figure 2-13, akin to the network overhead results, show the most dramatic deviations in the 10- and 20-node sparse-terrain scenarios. In these scenarios, network convergence times increase by more than an order of magnitude over their dense-terrain counterparts. In fact, in several of these scenario runs, convergence is never achieved during the 60-minute simulation. These results demonstrate that the relationship between long convergence times and high overheads is closely intertwined. When a network has weak connectivity due to degraded links (from terrain interference, low node density, etc.), SRW's proactive algorithms struggle to achieve a stable network structure. Poor links that waiver on the threshold of becoming full-fledged routing adjacencies are endlessly monitored with PROP messages, moving in and out of routing tables, as the waveform struggles to find an equilibrium. These high convergence times

further emphasize the effect and importance of node density on network performance, particularly when link quality is degraded.

6. Conclusions

Our simulations have shown that terrain interference and low node density can create overhead traffic levels that equal or exceed network data traffic demands. Link layer traffic suggests that both of these factors drive greater overhead messaging through their degradation of link quality. Under conditions of weak connectivity, SRW's proactive routing protocol creates excessive overhead as it struggles to monitor the quality of links and establish adjacencies with its neighbors. Even over the mild terrain of WSMR, attenuation and multipath interference is great enough to degrade signal strength and influence overhead message traffic. Reduced node density makes these terrain-degraded links even more tenuous by increasing the separation between nearest neighbors and decreasing the number of routing pathways. This observation is particularly relevant for SRW network design, as recent NIE events have replaced a single large SRW network with multiple small networks. Our results suggest that if these smaller nets subsequently cause reduced node density, this fragmentation could be counterproductive to overhead management given the degraded link quality we expect in many environments.

A true solution to SRW's overhead problem, as it relates to network scaling, would require a new approach to MANET design and a complete overhaul of the waveform. Given the time, money, and difficulty this change would require, SRW developers have chosen a less painful path which focuses on reducing the number nodes actively contributing to overhead traffic. Three methods are currently being pursued to accomplish the reduction in overhead in any one subnet:

1. *Breaking a battalion-sized network into many smaller SRW networks* – SRW network size, originally envisioned as 800 or more nodes, is now limited to 30 nodes for an operationally effective network. Although this change reduces overhead traffic, it also limits MANET functionality, requires additional spectrum, and complicates network management. A more detailed description of these changes and their impact is provided in Chapter 3.

2. *Implementing a "Voice-Only" Mode* – "Voice-Only" is a pared-down SRW mode that allows nodes to initiate and receive CNR calls, but deliberately inhibits all other data traffic. "Voice-Only" nodes are allowed to detect neighbors through Neighbor Discovery, but are inhibited from joining islands, establishing routing adjacencies, or transmitting network control messages. As a result, this mode could potentially provide CNR call capability to a large number of additional nodes without significantly affecting network overhead. The tradeoff for lower overhead is obviously a significant loss in functionality – "Voice-Only" nodes are invisible to their neighbors, unable to help heal the network, and unable to participate in data routing.

3. *Implementing a "Receive-Only" Mode* – "Receive-Only" is another reduced-functionality/low-overhead SRW mode that allows nodes to process network receptions but inhibits all transmissions. Similar to "Voice-Only" mode, "Receive-Only" nodes are allowed to detect neighbors through Neighbor Discovery but are inhibited from joining islands, establishing routing adjacencies, or transmitting network control messages. "Receive-Only" nodes may receive data traffic (PLI, CNR calls, other data messages), but they cannot relay these messages and they remain invisible to their neighbors.

The latter two modes allow SRW subnets to scale beyond current size constraints. For instance, a yet-to-be-verified Software Test Description (STD) test case targets a 90-node network consisting of 40 fully functional nodes, 45 "Voice-Only" nodes, and 5 "Receive-Only" nodes. Although overhead should be significantly reduced relative to a similarly sized network of full functionality nodes, further assessment is necessary to confirm the operational fit and value of reduced-functionality nodes. Even more importantly, we note that the increased scalability provided by these "-Only" modes does little to alleviate the network robustness and connectivity challenges faced by the 40 fully functional nodes. "-Only" nodes do not participate in MANET functions – they can't form routing adjacencies, they can't relay data, and they can't help isolated nodes rejoin the network. As a result, the addition of these nodes will not improve connectivity, and degraded link quality will continue to drive excessive PROP messaging under the conditions described in this chapter.

C. SRW Combat Net Radio Voice

SRW's Combat Net Radio (CNR) service provides an essential voice capability to dismounted soldiers and their support vehicles. This service replicates the type of legacy voice network offered by SINCGARS, while also providing range extension through a configurable number of neighbor node RF relays. Although CNR voice is an IP-like, packet-based service, its design and operation within the waveform are distinctly different from SRW's data services. Given the crucial role CNR voice plays in the warfighter's mission, this section provides an overview of SRW CNR operations, helping the reader to understand inherent implementation shortcomings that may influence voice call performance in the field.

In this section we explain CNR voice operation, utilizing M&S to demonstrate the point-to-multipoint broadcast behavior of a call. We show that because of the relay nature of CNR calls, call quality depends on the link quality of every intermediate hop. In a sparse network where the number of routes to a specific destination is limited, a single degraded link between two call participants could be detrimental to the call's performance. As such, breaking a large SRW network into several smaller SRW networks (i.e., the NIE network architecture) is particularly counterproductive for CNR call performance.

An additional concern raised in this chapter is the viability of SRW “adaptive equalizer” capability. SRW’s designers envisioned that in a topology where multiple retransmissions occur, these signals could be adaptively recombined to overcome the noise in degraded links. We reviewed this claim and, under our current assumptions, we question whether adaptive equalization will be physically achievable. Without a working equalization capability, CNR’s multiple retransmissions of the same call would increase the difficulty of signal processing, potentially hurting, rather than helping, call quality. A more detailed review of this capability is planned once IDA is granted access to the Information Repository (IR).

1. Combat Net Radio Description

SRW CNR is a push-to-talk, RF half-duplex, point-to-multipoint broadcast service. In this subsection we describe the design of CNR voice within the SRW protocol architecture and the broadcast behavior of global and local CNR voice calls.

Compared to SRW’s other packetized data services, CNR voice is unique in that it operates nearly independent of the SNDCF and Intranet layers (see Figure 2-14 for a depiction of CNR’s operation within the SRW protocol stack) and instead uses voice-specific applications (Voice Service and CNR Manager). Voice Service provides the interface between the Voice Codec and the lower layers of the waveform application and manages the push-to-talk interface. It provides voice packets for transmission and processes voice packets received from the CNR Manager application, which is responsible for call setup and maintenance. In addition, the CNR Manager acts as an intermediary between Voice Service and the Link layer, handling all incoming packets from the Link layer and passing along all outgoing packets that are to be forwarded on to other nodes.

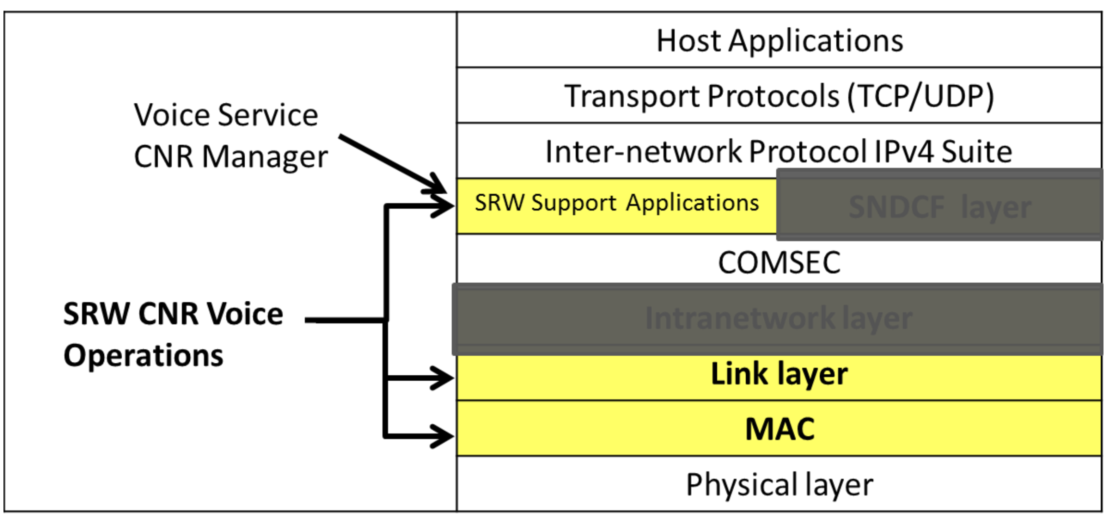

Figure 2-14. CNR Operations within the SRW Protocol Stack

When a user initiates a voice call, the Voice Service requests the services of the CNR Manager, which establishes a Time Division Multiple Access (TDMA) circuit for that call. A call circuit is typically allotted a 1.5- or 2.5-ms timeslot in each epoch (an

epoch is a collection of TDMA timeslots). Voice Resource Allocation Packets (VRAPs) are broadcast, notifying all nodes within the network of the new TDMA circuit. Once the circuit is established, any node that has been designated a "subscriber" of the call can transmit. All nodes in the network can act as relays, but only call subscribers can participate in the call.

2. Broadcast Behavior of Local and Global CNR Calls

CNR voice packets are transmitted via a "point to multipoint" broadcast over a logical channel designated specifically for voice traffic. This multi-relay transmission begins with a source node broadcasting voice packets to all its RF neighbors, in what we refer to as the initial "voice-hop." All of the receiving nodes in turn simultaneously relay the voice packet to their RF neighbors (the second voice-hop), and this process continues until the voice packet has reached the maximum number of "voice-hops" defined for the particular call type: local or global.

a. Global CNR Service

Global CNR calls are typically configured to have a maximum of four voice-hops. Global CNR provides voice circuits that may span multiple islands and have destinations in both tier 1A and tier 1B islands.

b. Local CNR Service

Local CNR calls are typically configured to have a maximum of two voice-hops. LCNR calls may also have destinations in tier 1A and tier 1B islands, but the calls cannot be relayed to another tier 1A island through tier 1B nodes. They may however cross tier 1A island boundaries directly if a call group member is in another island but within range of a relay node.[1]

In both global and local CNR, the broadcast behavior means that multiple copies of the same packet may be received within the same timeslot, and the same packet may be received in multiple timeslots. According to SRW 1.0C Waveform Design Specification [9] however, "SRW can precisely coordinate the retransmissions, which, when coupled with an adaptively equalized receiver, result in an additive benefit to the receiver…." Although the JCSS SRW model's behavior is consistent with this description, we are interested in operationally demonstrated effectiveness of this "adaptively equalized receiver." Further discussion of this topic is presented in the next section of this chapter.

3. JCSS Modeling of CNR Calls

In this section we present results from our JCSS modeling of SRW CNR calls. First we look at Link layer statistics to understand and verify the broadcast behavior we

[1] The ability to broadcast directly across tier 1A islands raises another concern for replacing a single SRW network with several smaller ones. Only a single network design allows all nearby nodes to act as relays; even those that belong to a different platoon.

described in the previous section. Then we examine how node placement and terrain may affect CNR call performance.

a. Point-to-Multipoint Broadcast Behavior

Point-to-multipoint broadcast behavior was studied using a 10-node, single-call scenario (see Figure 2-15). In this example, Node #1 (source node) places a 10-minute global CNR call to Node #9. The call initiates at simulation time, t = 5 minutes and terminates at t = 10 minutes. Nodes #1 and #9 are the only "subscribed" nodes in the call. Nodes #2-8 & 10 cannot participate in the call, but they can provide a relay.

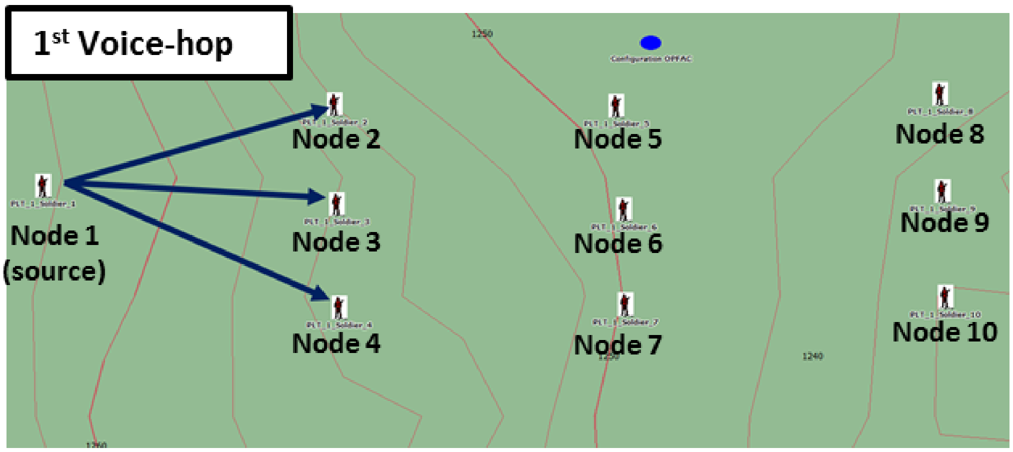

Figure 2-15. Network Topology for 10-Node Scenario with the First Voice-Hop Illustrated

Nodes #2-10 are separated into three groupings with the spacing between groupings such that each grouping is only within 1-hop RF range of its nearest neighbor groupings. For instance, the 2-3-4 node grouping is within 1-hop RF range of the source node and the 5-6-7 node grouping, but can only reach the 8-9-10 node grouping through an intermediate RF hop provided by the 5-6-7 node grouping.

The network is geographically located in the WSMR region. Terrain effects were modeled using TIREM4 propagation model and DTED specific to this region.

b. JCSS Link Layer Voice-hop Behavior

Figure 2-16 depicts the sequence of voice-hops for a single voice packet originating from the source node.

The first voice-hop is the broadcast of the packet from the source to its RF neighbors: Nodes #2-4. Each of these nodes receives one copy of the packet in same timeslot, which we will call reception timeslot A.[2]

[2] Since transmission and reception cannot occur in the same timeslot, timeslot "A" is a reception timeslot occurring after the original transmission timeslot. The second voice relay occurs in a transmission timeslot some number of timeslots after reception timeslot "A." Reception timeslot "B" occurs some number of timeslots after this second transmission timeslot.

The second voice-hop (Figure 2-16) is a broadcast from Nodes #2-4. This is a broadcast to their RF neighbors: Nodes #5-7, each receive three copies of the packet in the same timeslot, which we will call reception timeslot B; Node #1 (source node) receives three copies of the packet in timeslot B. The JCSS model results also imply that Nodes #2-4 receive two copies of the packet in timeslot B (this is the second timeslot in which they have received this packet).

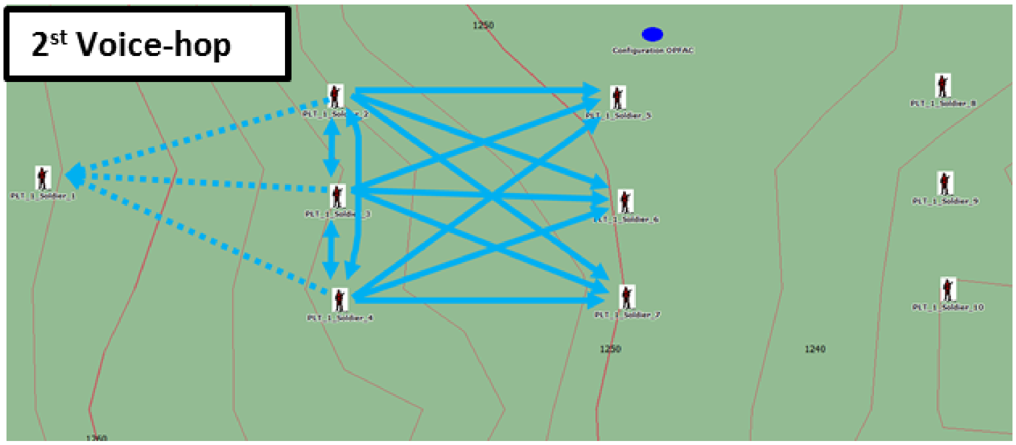

Figure 2-16. Second Voice-Hop for 10-Node Scenario

The third voice-hop (Figure 2-17) is the broadcast from Nodes #5-7. This is a broadcast to their RF neighbors: Nodes #8-10, each receive three copies of the packet in the same timeslot, which we will call reception timeslot C; Nodes #2-4 each receive three copies of the packet in timeslot C (this is the third timeslot in which they have received this packet); Nodes #5-7 also each receive two copies of the packet in timeslot C (this is the second timeslot in which they received this packet).

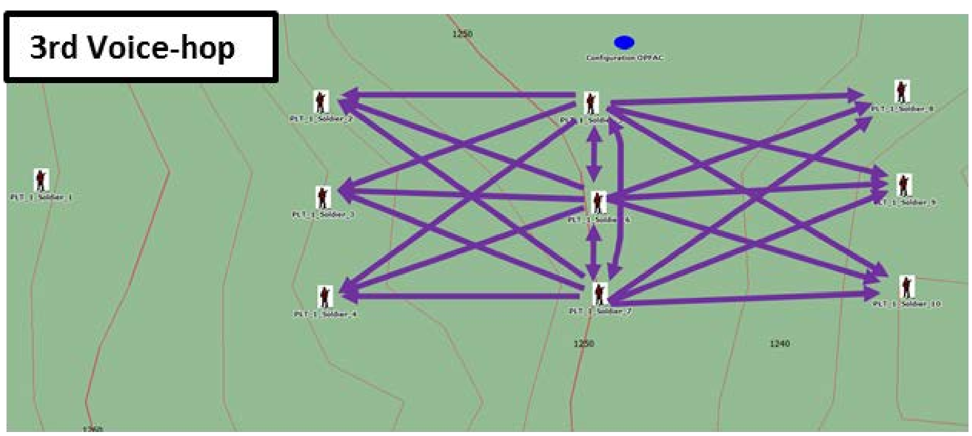

Figure 2-17. Third Voice-Hop for 10-Node Scenario

Note that although Nodes #2-4 received packets in timeslot B (and also in timeslot C), we have made the assumption that these nodes will not broadcast these packets again, i.e., nodes only broadcast packets one time, regardless of how many times they receive those packets. This assumption could not be verified in available SRW documentation but was supported by JCSS SRW model results.

The fourth and final voice-hop (Figure 2-18) is the broadcast from Nodes #8-10. This is a broadcast to their RF neighbors: Nodes #5-7, each receive three copies of the packet in the same timeslot, which we will call reception timeslot D (this is the third timeslot in which they have received this packet); Nodes #5-7 also each receive two copies of the packet in timeslot D (this is the second timeslot in which they received this packet).

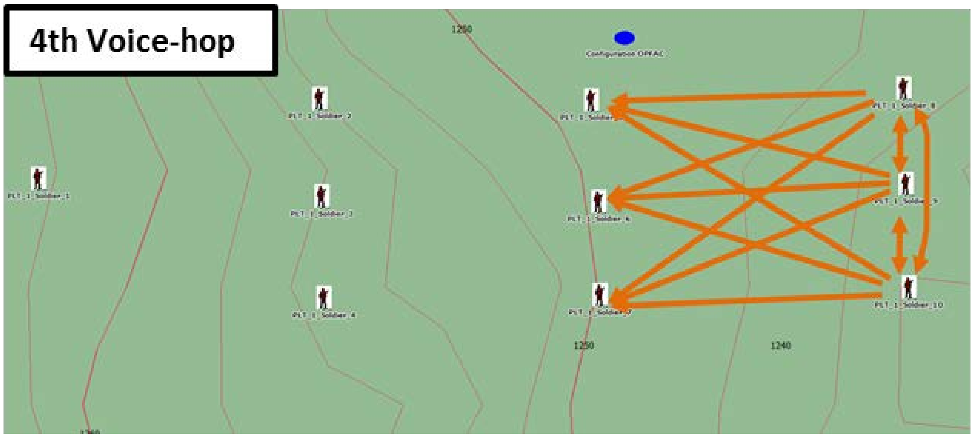

Figure 2-18. Fourth Voice-Hop for 10-Node Scenario

Let's start our analysis of this simulation by observing that CNR voice traffic is sent at 42.5 kbps for 10 minutes (an unrealistically long call, but used here simply for illustration purposes.) (See Figure 2-19.) Next let's consider the Link layer activity for a non-subscribed relay, Node #3 (Figure 2-20). From our previous voice-hop discussion, we know that Node #3 will be receiving six copies of every voice packet at the physical layer (see left side of Figure 2-20). At the Link layer, however, we see received traffic of only 127.5 kbps, or three times the source transmission rate. Why the difference? It appears SRW's "adaptively equalized receiver" is able to "precisely re-coordinate" transmissions that occur in the same timeslot. Node #3 receives the same voice packet up to three times in three different timeslots (each arrow in Figure 2-20 represents a different transmission; the arrow color, a different timeslot). The adaptive equalizer is able to combine the two transmissions received in timeslot B (light blue) and similarly the three transmissions in timeslot C (purple), giving a received Link layer traffic of three times the source transmission rate. From the SRW documentation available to us, it's unclear exactly how this Link layer traffic is subsequently processed, but we believe only the first packet reception (timeslot) is used. Later timeslot receptions are simply discarded. As a result, Node #3 relays voice packets at the original data rate, 42.5 kbps.

This Link layer behavior is further confirmed by the activity for Node #9 (the call subscriber) shown in Figure 2-21. Here each voice packet is received a total of five times (across two timeslots) at the physical layer. The adaptive equalizer combines the three transmissions received in timeslot C, and similarly the two transmissions in timeslot D, giving a received Link layer traffic of two times the source transmission rate. Even though this node is a subscribed node, it still relays the call in case another subscriber sits beyond the range of the previous voice-hop. Since the voice packets arriving at Node #9

have all traversed at least three voice-hops, the relay provided by Node #9 is the fourth and final relay.

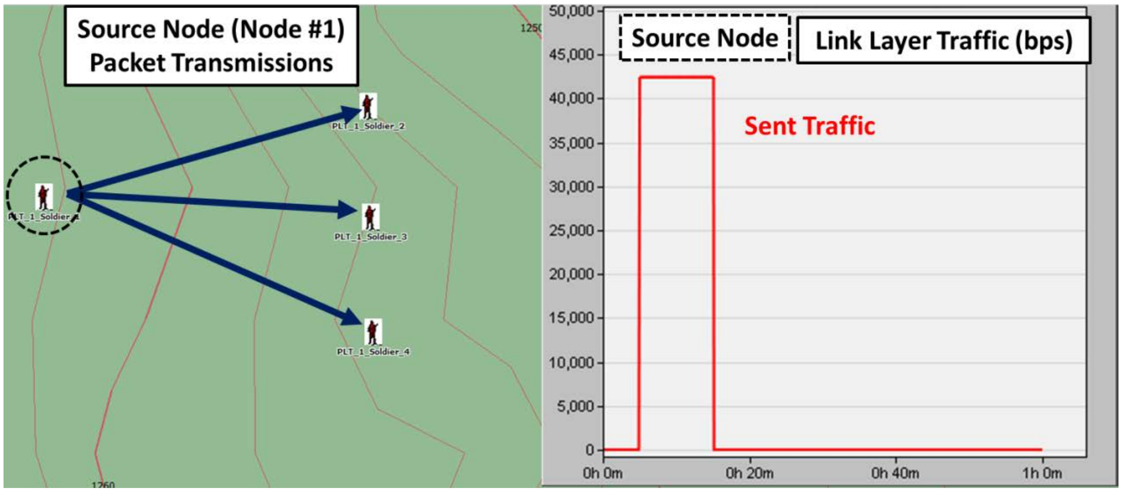

Figure 2-19. Voice Traffic Sent by the Source Node (Node #1)

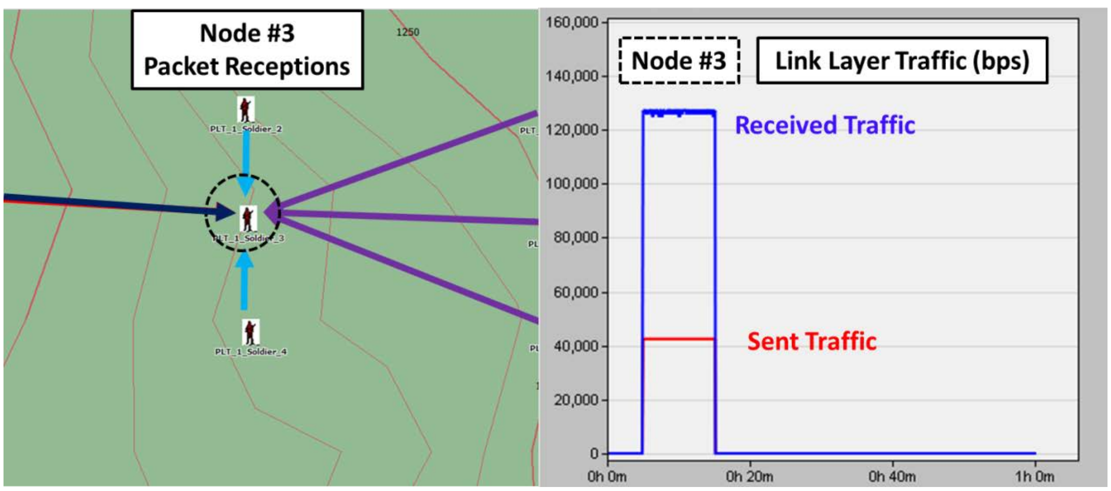

Figure 2-20. Voice Traffic Sent and Received by Node #3

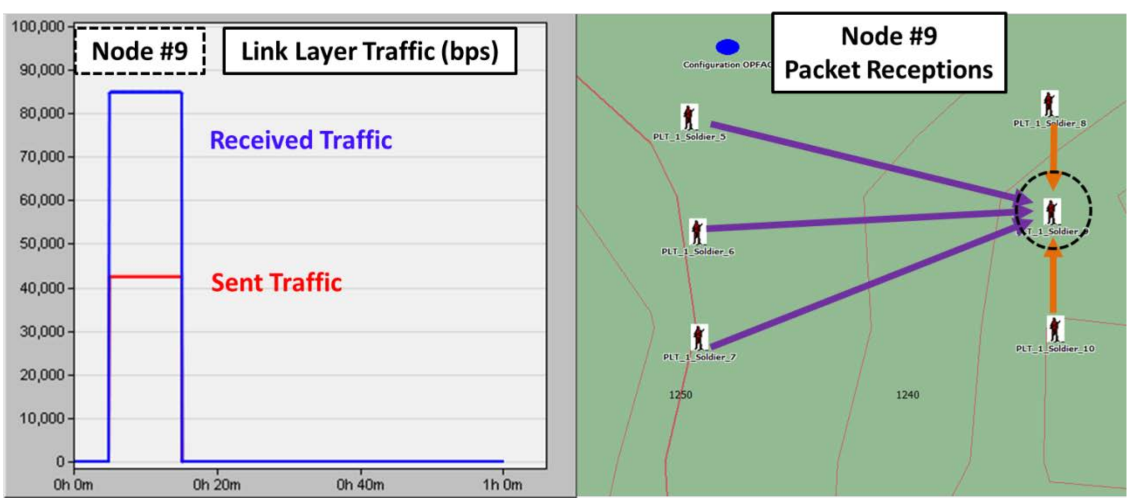

Figure 2-21. Voice Traffic Sent and Received by Node #9

c. SRW's Adaptive Equalizer Issue

In the previous subsection, an important part of our interpretation of CNR call behavior is based on the following statement found in MIT Lincoln Laboratory's analysis of SRW networking behavior and performance: "SRW can precisely coordinate the transmissions, which when coupled with a receiver with an adaptive equalizer, result in an additive benefit to the receiver…."

The statement implies that multiple nodes can transmit the same information within the same timeslot because all the nodes are aligned by the network time alignment process, and the equalized sum of all transmissions will be correctly demodulated. This principle appears to be impractical in light of actual physical layer principles. In this subsection we describe why this seems an impractical requirement for physical layer implementation of SRW voice.

1) Physical Layer Assumptions

We base our assumptions of the SRW physical layer implementation on the documentation that was available to us. The following is a list of our assumptions regarding the physical layer:

- Packet timeslots are either 1.5 or 2.5 ms [9].
- Timeslots within the network are aligned to ±1 μs [9].
- Voice is transmitted in a non-spread-spectrum mode – CC modes #1 (2.0 Mbps) or #2 (0.937 Mbps). SRW also allows for two spread-spectrum CC modes, but with much lower data rates, which are likely too slow to support voice traffic. If voice is transmitted in a spread-spectrum mode, adaptive equalization would be more feasible (though not a certainty) than what we demonstrate in this discussion.
- Baud time (symbol duration):
  - 0.500 μs for CC Mode #1 (2.0 Mbps)
  - 0.833 μs for CC Mode #2 (0.937 Mbps)
- The In-phase and Quadrature (I/Q) sampling of the received waveform is assumed to be 2.4 Msps. (The SRW WDS states sampling is twice the symbol rate for non-spread CC [9].)
- The local Voltage Controlled Crystal Oscillator (VCXO) has an accuracy of 1 parts per million (ppm), and therefore the worst case potential frequency offset of a 1 GHz carrier frequency when carried by a soldier is 2 Hz (1Hz for the transmitting source and 1 Hz for the receiver) if the soldiers are both stationary and ± 8Hz if they are walking at normal walking speeds (1 m/s). Thus all respondents will begin to transmit their individual copies of the packet information within 1 μs of each other. Some copies can be up to one symbol

early or one symbol late relative to a nominal network standard timeslot alignment.

2) Physical Layer Implication Issues

The operational utility of an adaptive equalizer is such that it will acquire phase and magnitude of various multipath components so that they can be added together coherently within the same symbol, and that multipath components that arrive during a subsequent symbol can be subtracted or canceled. Typically this adaption process is relatively slow or is acquired during the packet preamble. In SRW, the equalizer is integrated into a proprietary error-correcting code developed by Trellisware. It is assumed that it equalizes four taps. Since the equalizer provides two samples per symbol, under nominally perfect conditions this works as an equalizer over one signal component arriving within two symbols from the direct and multipath reflections. For non-spread CC modes, I/Q sampling only provides two samples per symbol. This is the minimum sampling for a single signal component (Nyquist criterion). Equalizing several signal components will be unmanageable even under nominally perfect conditions. However, (1) frequency offset randomizes the phase angle of the carrier frequencies, and (2) a sufficient number of nodes create both early and late components that will exceed the capacity of the equalizer to find phase and magnitudes to coherently combine all arriving signal components. Given the random nature of multiple arriving signals component vectors, there will sometimes be constructive combining and sometimes destructive combining. As the number of signal components increases, the central limit suggests that destructive combining will occur more frequently.

Because the details of the Trellisware equalizer are unknown, it is unclear whether it can track both the frequency offset of the direct path and the corresponding Doppler offsets of multipath components (moving multipath reflections can cause Doppler frequency offset relative to the direct path – a vehicle can introduce ± 88 Hz of Doppler). More importantly, it is also unknown whether this equalizer can track and cancel early and late signal components relative to the strongest signal component from the closest node. If not, there can be strong interference from other nodes sending the same data but with the data appearing one symbol time early or late. If the equalizer is unable to handle both within symbol and early/late signal components then early or late signal components relative to the strongest signal will introduce bit errors.

Finally, let us consider frequency offset. At any given time the RF carrier phase of one node is random relative to the phase of all other nodes as a result of frequency offset. A receiver can acquire the phase of that carrier after it propagates from one transmitter to one receiver. This phase acquisition is accomplished in part by the transmission preamble. However, when multiple nodes send the same waveform, there is a probability that the phase and magnitude of all signals when combined at one given location will sum to a much smaller number than any single version of the signal due simply to the phase vectors nearly cancelling each other (vector sum to a relatively smaller number). This is

a purely random process and is likely to produce a different vector sum for every transmission. Using a frequency offset of 8 Hz as an example, and with only two nodes transmitting, and being received at equal magnitude at some location, the signals would sum to nearly zero every 125 ms. There would not be sufficient signal strength for an equalizer to be able to pick out a direct path and an alternate path.

Thus, based on the above assumptions, there appear to be two mechanisms, frequency offset and early/late signal components, which will randomly introduce conditions that will occasionally appear as link breakages. Unfortunately, our simulations are unable to either confirm or refute this behavior. This is due to two reasons: (1) frequency offset doesn't exist in network simulation, and (2) it is unlikely that the "adaptive equalizer's" interaction with the physical layer was modeled with sufficient fidelity to capture these effects. In real-life operation, however, we do expect that without any unique spreading code to enable signal separation, CNR call quality may be degraded when multiple nodes relay the same message at the same time.

4. Call Quality Issues and Network Topology

In this subsection, we will discuss simulation configuration, the effect of node placement on call quality, and the effect of terrain and network architecture.

a. Simulation Configuration

The effects of node spacing and terrain on call quality are demonstrated with simple three-node, single-call scenarios. In these scenarios (shown in Figure 2-22), Node #1 (source node) places a global CNR call to Node #3, that initiates at simulation time, t = 10 minutes and terminates at t = 40 minutes. The 30-minute call length was chosen to confirm that the observed call behavior was not transient. Nodes #1 and #3 are the only subscribed nodes in the call. Node #2 cannot participate in the call but provides a necessary relay.

In scenario A, the nodes are laid out in a string topology with inter-node spacings of approximately 1 km, as shown in Figure 2-22. In scenario B, Node #1 remains in the same position as in scenario A, but Nodes #2 and #3 have been shifted closer to Node #1. The inter-node spacing between Nodes #2 and #3 remains identical. In both scenarios, Node #1 cannot reach Node #3 in a single hop and therefore it must use Node #2 as an intermediate relay. Figure 2-23 shows the terrain profile of the link between Node #1 and Node #2 in each scenario. Terrain effects were modeled using TIREM4 propagation model and WSMR DTED.

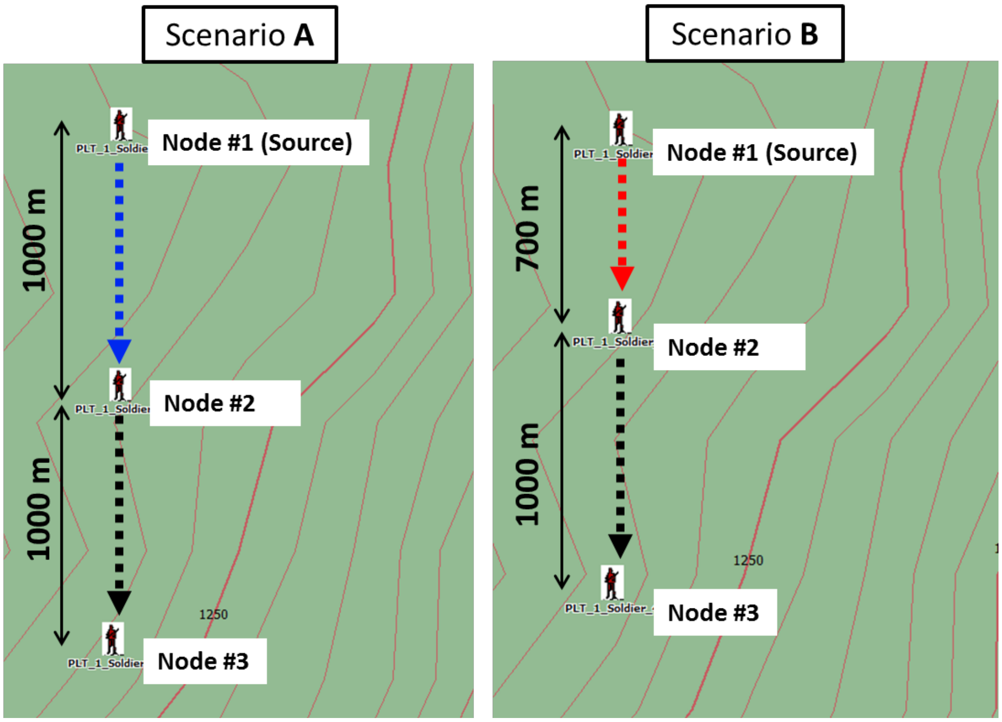

Figure 2-22. CNR Call Configuration for Scenario A and B

In these scenarios, the source node (Node #1) transmits a call, which is received by Node #2 and relayed on to Node #3. In scenario B, Node #2 and Node #3 are located 300 meters closer to Node #1. The relative spacing between Node #2 and Node #3 remains unchanged.

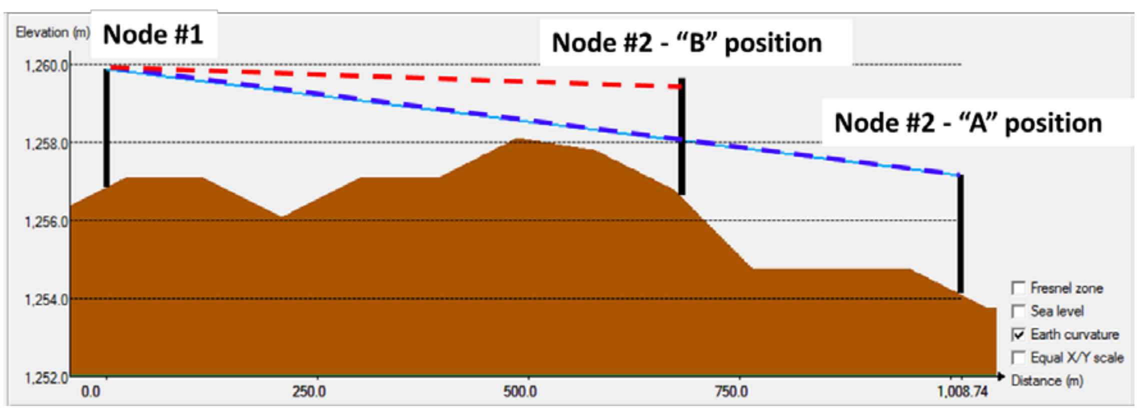

Figure 2-23. Terrain Profile of Link between Node #1 and Node #2 in Scenarios A and B

b. Effect of Node Placement on Call Quality

Figure 2-24 shows that Node #1 transmits voice data at 42.5 kbps for 30 minutes during both scenarios. In Figure 2-25, the received link layer traffic for Nodes #2 and #3 is plotted. In scenario A, Node #2 receives the transmission from Node #1, but the call quality is somewhat degraded (notice the noise in the received transmission). The subsequent relay transmission to Node #3 also exhibits degraded call quality.

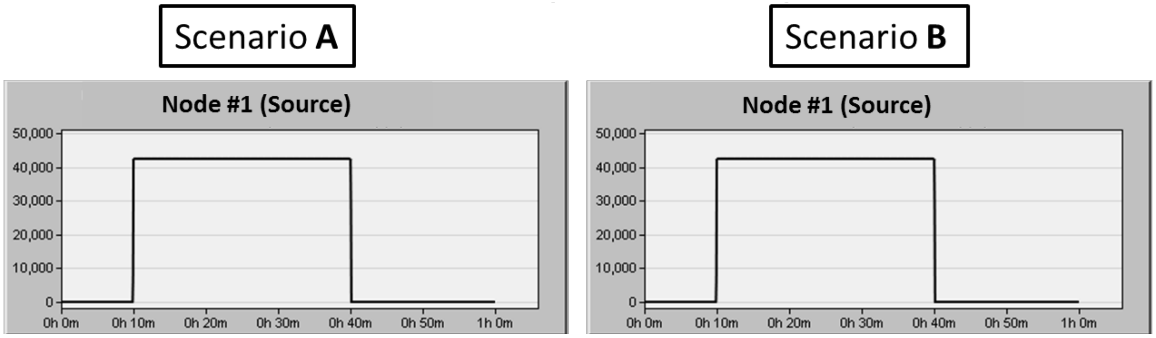

Figure 2-24. Voice Traffic (Link Layer) Sent from Source Node (Node #1)

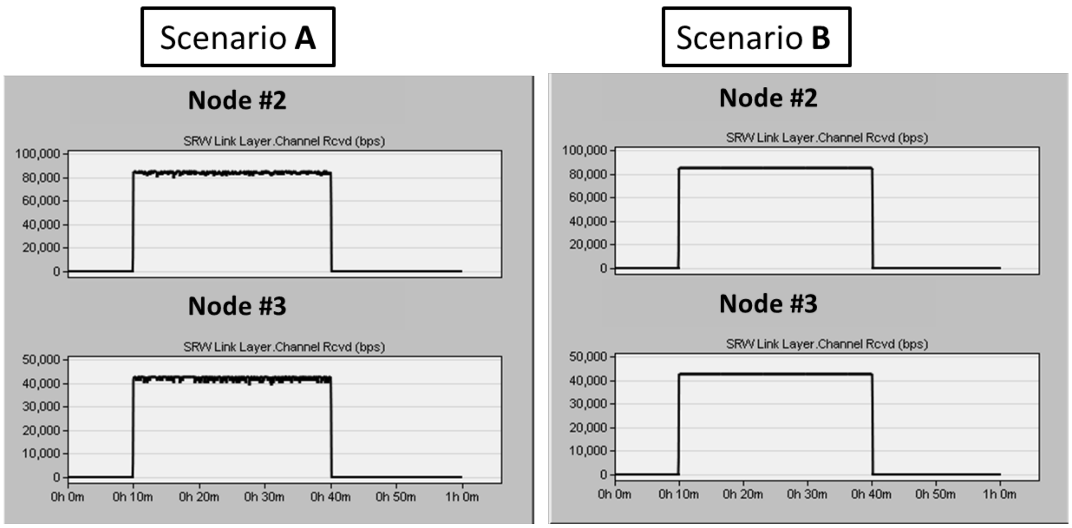

Figure 2-25. Voice Traffic (Link Layer) Received by Node #2 and Node #3

Why is there noise in these transmissions? Terrain attenuation and interference degrades the link quality between Nodes #1 and #2. If Node #2 is moved 300 meters closer to Node #3 (scenario B), the attenuation decreases by 9 dB (Figure 2-26) and the noise in these transmissions disappears.

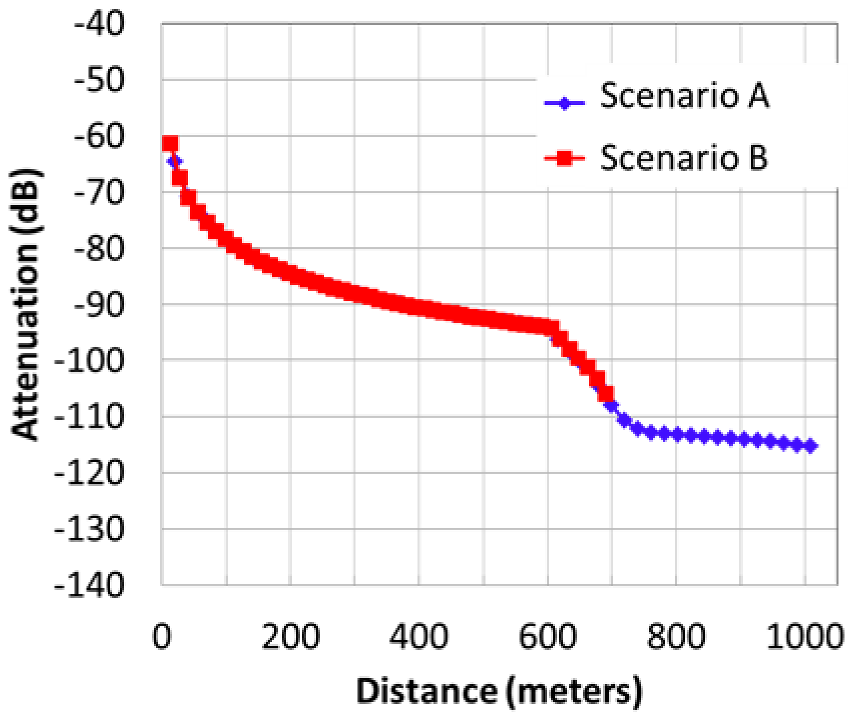

Figure 2-26. Signal Attenuation as Function of Distance between Node #1 and #2

Signal attenuation was calculated in OPNET using DTED and the TIREM4 propagation model. Additional specifications: operating frequency of 2,000 MHz, 1.2-MHz bandwidth, and 3-meter antenna height.

c. Effect of Terrain and Network Architecture

While it should come as no surprise that terrain effects can impact the quality of CNR calls, these results warrant additional discussion. First, it's important to emphasize that due to the relay of nature CNR calls, call quality depends on the link quality of every intermediate hop. In a sparse network, where the number of routes to a specific destination is limited, this is a particularly relevant concern. A single degraded link between two call participants could be detrimental to the call's performance. Breaking a large SRW network into several smaller SRW networks (i.e., the NIE network architecture) is particularly counterproductive for CNR calls. Although CNR calls may relay directly across tier 1A islands, they are not capable of propagating across *different* SRW networks. As a result, under the NIE network architecture, a node in 1st Platoon would not be able to relay through a node in 2nd Platoon, even if that node offered the best (or only) pathway to the destination node.

5. Conclusions

The M&S study described in this section demonstrated the unique point-to-multipoint broadcast behavior of SRW CNR calls, highlighting how terrain and sparse network design can affect call performance. For a dense network, where many relay routes exist, we described additional concerns related to SRW's "adaptive equalizer." SRW's designers envisioned that, in such a topology, multiple retransmissions could be adaptively recombined to overcome the noise in degraded links. As our discussion noted,

however, in the absence of a spread-spectrum voice capability, this adaptive equalization may not be physically achievable. Without a working equalization capability, CNR's multiple retransmissions of the same call would increase the difficulty of signal processing, potentially hurting, rather than helping, call quality. IDA recommends a more detailed review of this capability, provided that more detailed information regarding the algorithm and its implementation on specific radio systems could be made available.

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3. Discussion

A. How Does the Physical Environment Challenge SRW (and All Radio Waveforms)?

In this chapter we review the fundamental physical constraints that limit all radio performance with an emphasis on signal propagation behavior as a function of environment (terrain, foliage, urban blockages) and operating frequency. This analysis is intended to be general, as actual radio performance will depend on specific details of the gain, modulation, and processing used to improve the signal. We do, however, highlight that specific challenges are posed by higher-frequency communications. New tactical waveforms like SRW continue to trend toward frequencies that are significantly higher than those used by legacy waveforms. This shift is motivated by greater throughput demands due to increasing data transfer requirements (more voice, message, and video traffic) as well as increased networking management loads (proactive routing and monitoring). Although higher frequencies offer larger bandwidths to accommodate these demands, their propagation through the physical environment can be more tenuous, ultimately limiting their functionality. In this analysis, we discuss the fundamental principles that underpin these issues of operating frequency, loss, and interference. We conclude this chapter with a comparison of MANETs and cellular networks to explain the nature of the challenges that the former faces relative to the latter.

1. Throughput

The throughput-frequency relationship driving new tactical waveforms to higher and higher frequencies is governed by the Shannon-Hartley theorem, which describes the maximum data transfer rate for a communication channel. The channel capacity, C, is given by:

$$C = B\log_2(1 + SNR), \tag{3-1}$$

where B is the bandwidth and SNR is the signal-to-noise ratio. Since the bandwidth available for a communication channel is a fraction of the operating frequency, higher operating frequencies provide larger bandwidths. In the plot below, we show the maximum channel capacity (throughput) as a function of bandwidth (or alternatively operating frequency) and SNR.

Although real throughput values depend on the specific details of the signal's modulation, attenuation, and interference, Figure 3-1 still provides insight into general behavior trends. Channel throughput increases linearly with bandwidth (and therefore operating frequency), but just as importantly, we see that throughput is also highly

dependent on SNR (and therefore the quality of the link). In the next section, we discuss how the physical environment affects SNR, analyzing how loss and interference can degrade the transmitted signal.

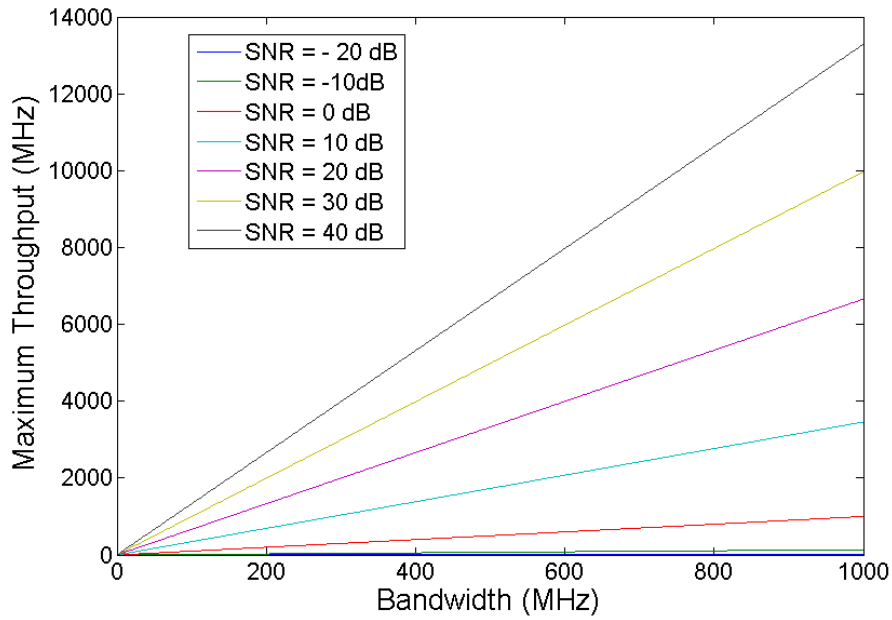

Figure 3-1. Theoretical Maximum Throughput for a Single Channel or Specified Bandwidth and Signal-to-Noise Ratio

2. Signal Loss

As radio waves propagate, a number of mechanisms may cause scattering, reflection, diffraction, or absorption of the transmitted signal. In the link budget, the effect of these mechanisms to reduce the received signal power is referred to collectively as "losses." In this section, we discuss the principal sources of these losses and other interference in the physical environment.

a. Free-space Path Loss

As a radio wave travels from the transmitter to the receiver, there is always a reduction in power due to the spreading of the radio wave in space, referred to as free space path loss (FSPL). For an isotropic transmitter, the signal power density (S), at distance (d), decreases according to the inverse square law:

$$S = P_t \frac{1}{4\pi d^2} \tag{3-2}$$

where P_t is the signal power at the transmitter. The signal power received by an isotropic antenna depends on the signal power density (S) at the receiver and the antenna's effective area, a function of frequency (f), according to the following relation:

$$P_r = S \frac{c^2}{4\pi f^2} \tag{3-3}$$

where c is the speed of light. The ratio between the transmitted and received power is the FSPL and is given by:

$$L_{fs} = \left(\frac{4\pi d f}{c}\right)^2 \tag{3-4}$$

This relation shows that FSPL increases with the square of frequency. As result, higher frequency signals will be attenuated much more than lower frequency signals. Figure 3-2 provides a graphical comparison of FSPL for MANET and legacy waveforms. The high frequencies of SRW and WNW provide larger channel bandwidth, but this comes at the expense of increased attenuation that, in turn, reduces their SNR and range in comparison to legacy waveforms.

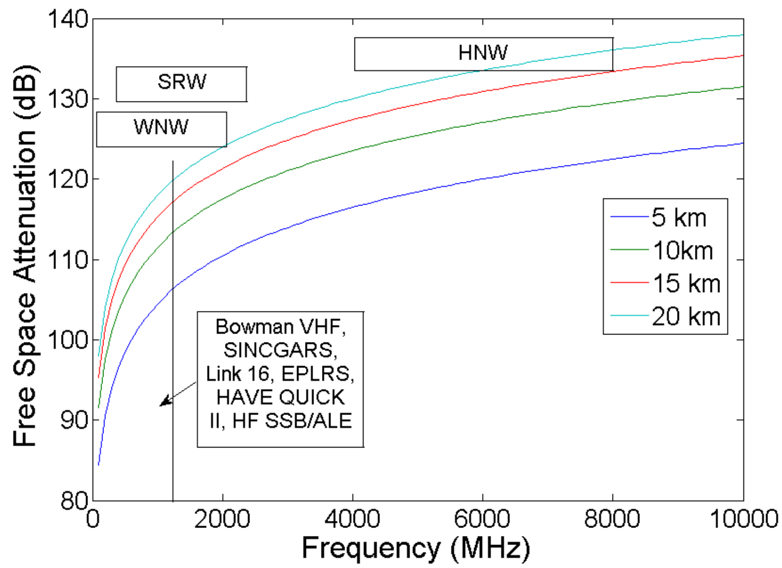

Figure 3-2. Free Space Attenuation as a Function of Frequency and Range

Tactical waveform names overlay the frequencies at which they operate. There is no significance to their position relative to the *y*-axis.

b. Multipath Interference

The previous section considered a signal in "free space," which could propagate without interference. Now we consider a real environment where there exists a multitude of terrain, trees, buildings, and other features that could block or degrade the signal. Line-of-sight blockages are obvious sources of interference, but non-line-of-sight features can also severely degrade a signal due to multipath interference. Multipath interference occurs when radio waves reflect or refract off terrain features, creating multiple signals that arrive at the receiver out of phase, making it more difficult to correctly process the arriving signals.

It is generally recommended for radio communications that at least 60 percent of the first Fresnel zone radius (Figure 3-3) be free of obstructions in order to minimize multipath interference. The radius of the Fresnel zone at any point P is given by:

$$F_n = \sqrt{\frac{ncd_1d_2}{f(d_1+d_2)}} \tag{3-5}$$

where d_1 is the distance from node 1, d_2 is the distance from node 2, c is the speed of light, f is the frequency, and n is the n^{th} Fresnel zone. From this relationship, we see that size of the Fresnel zone is inversely related to frequency; therefore, over the same set of terrain features, lower frequencies will experience greater multipath interference than high frequencies.

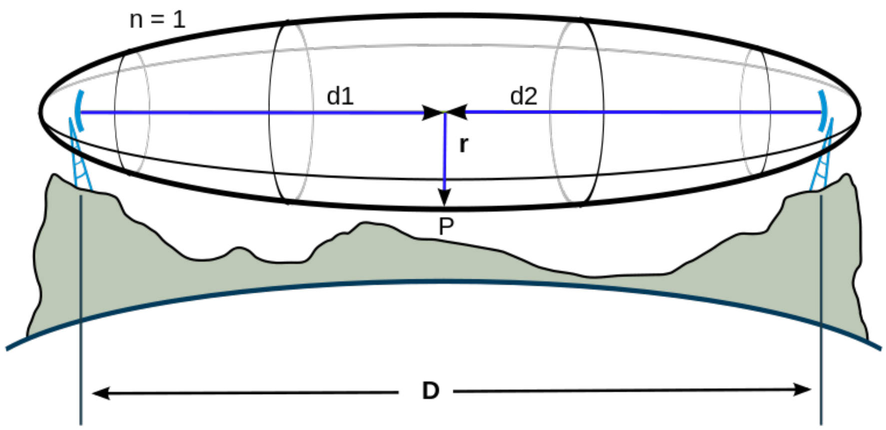

Figure 3-3. Fresnel Zone [12]

To minimize multipath interference, the first 60 percent of the first Fresnel zone should be clear of obstructions. The maximum radius, r, of the Fresnel zone occurs at the location, P, which is equidistant from the left and right antennas (d1=d2).

To illustrate the effect of antenna height on multipath interference, we plotted the maximum radius of the Fresnel zone as a function of frequency in Figure 3-4. To avoid interference from flat ground, the antenna height must be greater than 60 percent of the radius listed on the *y*-axis. As an example, to communicate a distance of 1 km at a frequency of 2 GHz (within the upper operating frequencies of SRW), the antenna must be at least 3.5 meters high, just to avoid interference from flat ground. For lower frequencies and larger communication ranges, the required antenna heights grow even higher, quickly exceeding heights that are practical for a mobile, combat suitable communication system.

Choosing an appropriate operating frequency involves an interesting tradeoff between FSPL and Fresnel zone interference: lower frequencies provide the least FSPL, but they experience the greatest Fresnel zone interference for a given antenna height. As a result, the performance of dismounted and mounted radios operating at the same frequency will be different. For instance, at a lower frequency, dismounted radios with their short antenna heights may be overwhelmed by Fresnel zone interference, but a mounted radio, which is able to avoid this interference, can actually propagate a signal that benefits from the reduced FSPL of that lower frequency. This relationship may explain why at NIE 14.1, SRW platoon and company networks were assigned to L-band and UHF frequencies, respectively. Since platoon networks, as compared to a company

network, are composed of a greater fraction of dismounted nodes and are likely to have a smaller inter-node spacing (such that a shorter transmission range is acceptable), the higher frequencies of L-band may have offered a more desirable tradeoff in performance.

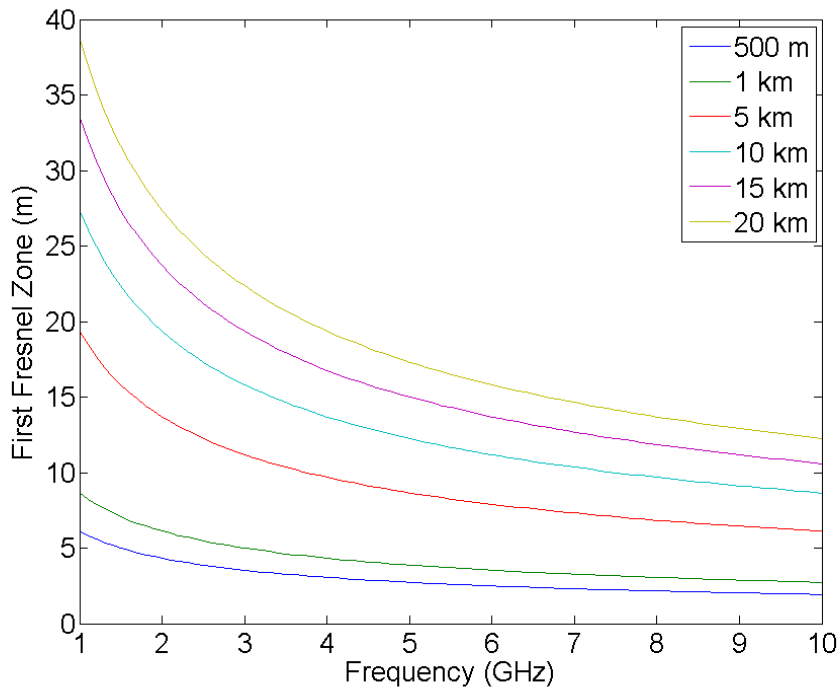

Figure 3-4. Maximum Radius of the First Fresnel Zone as a Function of Frequency and Range.

To reliably communicate, 60 percent of the first Fresnel zone radius must be from free from obstruction. For a SRW radio operating at 2 GHz and a distance of 1 km, antennae must be at least 3.5 meters high to avoid interference from flat ground.

c. Atmospheric Absorption

Water vapor and oxygen molecules present in the atmosphere can also contribute to radio wave attenuation. The amount of loss is dependent on the density of molecules in the air, propagation distance, and signal frequency. Absorption is greatest near these molecules' resonant frequency: 22.3, 183.3, 323.8 GHz for water vapor; 57-62 GHz and 118.74 GHz for oxygen. Since these frequencies are much higher than those of MANET and legacy waveforms, atmospheric absorption is unlikely to be a significant component of their attenuation.

d. Foliage

In forested environments, foliage is a significant source of signal interference. The degree of attenuation depends on the density and size of the foliage, the angle of transmission, and the path length through the vegetation. While analytical models do exist, precise prediction of foliage attenuation is difficult and highly dependent on the situation. In general, it is accepted that loss increases with signal frequency, and empirical measurements suggest that attenuation is on the order of dB per meter for signals in the low GHz range.

e. Urban Blockages

Our analyses prior to this point have focused on the effects of natural terrain, ranging from desert to mountain and foliage, as the setting for MANET operation necessarily includes this environment, and the majority of testing has taken place in such environments as Fort Bliss and White Sand Missile Range. However, the urban environment is also relevant, and contains several additional features that introduce challenges to communications. We evaluate here the models used to apply to cellular systems as a first look into the expected performance in an environment cluttered with man-made structures. The main difference between the results will depend on antenna height, as cellular models assume the base station antenna is transmitting from a highly advantaged point. In the last section, we will evaluate the transmission of a signal from outside to inside a man-made structure to gain insight into the "CACTF Attack" mentioned previously.

1) Urban Models

Electromagnetic propagation in an urban environment is a complex problem that cannot be exactly solved. Accurate ray tracing would require exhaustive modeling of the details of the environment, which is generally unavailable. The signals, similarly, are a complicated superposition of scattered radio waves. However, by treating the signal statistically, and the environment as a repeating, homogeneous set of features, theoretical models such as the *Diffracting Screens* model [13] can be used to garner insight into the behavior and power demands of personal communication systems in urban and suburban environments. Alternatively, empirical models based on measurements made in real environments are often used to develop curves that can then be used to predict trends in behavior. The most commonly used data set is that collected by Y. Okumura [14] in Tokyo, Japan. From this empirical model, M. Hata [15] developed a formulaic representation that can predictively estimate losses as a function of frequency, antenna height, terrain type, and range. Correction factors are used to modify the formula for a specific application. For the purposes of this discussion, we will utilize the models developed by Hata to investigate path loss of an SRW-like signal in an urban environment. First, we look at path loss in a generalized urban environment and then at propagation within buildings. The loss predicted by the Hata formula is expressed as

$$L_{mh} = -(L_{ccir} + S_0 - S_{ks} + B_0) \tag{3-6}$$

where L_{ccir} is the basic formula for the median path loss, S_0 and B_0 are terms to incorporate the density of structure in the environment, and S_{ks} is the correction for the Earth's curvature.

The comparison of the modified Hata formula and the empirical data is shown in Figure 3-5. At short ranges and at the frequencies used by SRW (225-2500 MHz), we see very good agreement between the model and the data. However, the base station antenna height (H_b = 200m) is significantly higher than that used by the mobile radio

system and is validated for a minimum of 30 meters, and the receiving station antenna height (H_m = 3 m) is appropriate for mobile vehicle use of SRW.

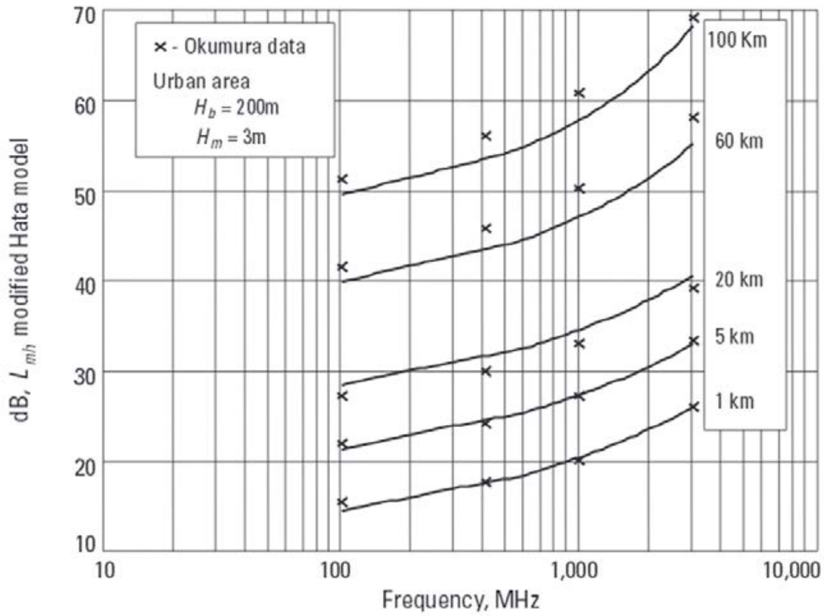

Figure 3-5. Comparison of the Modified Hata Model with Okumura Data [13]

Reading directly off the chart above, in the frequency ranges of interest for SRW (225-2500 MHz), we see that *if* SRW were being transmitted by an advantaged node in an urban area, at ranges of 1-5 km, attenuation due to the man-made structures would be in the range of 15-35 dB. This provides a lower bound on attenuation in the real scenario, where transmission is peer-to-peer from 1- to10-meter-high antennas.[1]

2) "CACTF Attack" – Case Study for Propagation into a Building

During NIE 14.1, a platoon leader entered a building using his SRW mobile radio; upon entrance into the building, signals were lost. Here we look at the specific scenario of a receiving antenna inside of a building and a transmitting antenna outside to understand the effect of the building itself on this specific scenario. When the receiver is inside an urban structure, signal loss is affected by factors such as the type of building, its construction, and the floor level. Data were collected for a variety of building types and range of frequencies by Turkmani [16] and are displayed in Figure 3-6. The three different building types explored in Reference 16 are urban: large downtown office and commercial buildings; medium: medium-sized office buildings, factories, and small apartment buildings; and residential: one- and two-level residential buildings, small commercial and office buildings.

[1] The shape of the curve is also likely to differ in the case of no advantaged node (MANET) scenario.

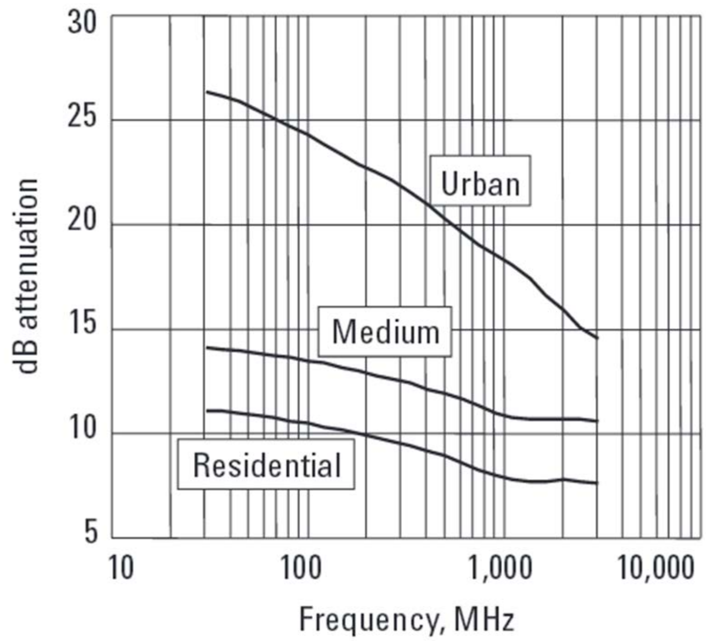

Figure 3-6. The Additional Attenuation Introduced When Transmission Is from Outside to Inside a Building [16]

One can see that the attenuation due to the building structure itself decreases significantly as frequency increases. In the operating range of SRW, the attenuation ranges from approximately 23 dB (outside to inside) to 7 dB (based on building type and frequency). The information obtained regarding the physical structure in question in the NIE scenario is insufficient to evaluate the specific attenuation in that environment but is likely addressed by the *medium* building type. Depending on original signal strength and attenuation prior to reaching the building, an additional loss of 12-13 dB (medium structure, UHF-band) may have been sufficient to degrade the signal below a minimum threshold of usability. If the SRW links upon which that node was dependent were already weak, this additional attenuation could effectively shut off communications capability to the radio in question. However, this level of attenuation in the context of a radio with a transmit power as high as those expected from SRW radios is unlikely to have been catastrophic in its own right. Absent a direct measurement, we could also attribute this loss of connectivity to a number of other sources of dysfunction, at either the hardware or software level.

For example, our investigation into the CACTF incident uncovered an issue that (unlike urban attenuation or network planning) is internal to the waveform itself. During a recent discussion with representatives of the Joint Tactical Networking Center (JTNC), we learned that a hysteresis problem had been corrected in recent versions of SRW. The waveform is designed such that when a link is dropped, the link strength must improve above a specific threshold before the link will be reestablished. In earlier releases of SRW, this threshold was set unnecessarily high, requiring nodes to come very close to one another to reestablish the link. If the platoon leader and company commanders were

operating radios without this hysteresis fix, attenuation may have been too great for them to reconnect as quickly as needed. If this was the case, we note that this software issue could have played an equal if not greater role in the CACTF incident than any of the other factors (urban attenuation, network planning) discussed previously.

An interesting wrinkle with the hysteresis issue is that most, but not all, contractors corrected the problem in later SRW versions they ported to their devices. In particular, General Dynamics (GD) neglected to (or chose not to) implement the fix despite JTNC's specific guidance to do exactly that. GD's Rifleman Radio continues to run SRW v1.01.1 (current version is v1.2.1), which notably lacks both the hysteresis fix and an important update addressing a "voice-check" issue. This indicates that the radios are not necessarily entering operational test with the most up-to-date versions of the waveforms. Although this example of a possibly outdated waveform version may be an unusual one, it does suggest that there may be benefit to improving communication of software fixes among the waveform development community and test community and contractors. It may not be realistic for waveform updates and program test schedules to always align, but we should expect the testers to be kept apprised of issues addressed in the newest releases, and how those might affect the test outcomes. By doing so, the test community can recognize performance issues caused by these flaws, consider whether a fix has been successfully implemented in a later version, and make a more educated appraisal of the system's performance. Just as importantly, this knowledge should also help testers avoid wasting resources on test scenarios where these issues are known to cause performance problems.

3. MANETs vs. Cellular Networks – Why Are MANETs at a Disadvantage?

Our expectations for MANET performance are often influenced by our personal experiences with cellular networks, where ubiquitous connectivity brings streaming video into the palms of our hands. As years of operational testing have demonstrated though, these expectations are considerably harder to meet when subject to the constraints of a mobile, tactical network. Cellular networks benefit from a fixed infrastructure of base-station towers that are not restricted by the size, power, and weight requirements of mobile radios. These towers provide tremendous link budget advantages through their great antenna height, antenna gain, and transmit power. Furthermore by off-loading network management to base station controllers, a higher percentage of the link throughput can be used for actual data transmission. MANETs and cellular networks may be similar in their operating frequency and modulation schemes, but it's the differences in infrastructure that drive the huge performance disparity between the two networks. In this section we provide a general comparison of MANETs and cellular networks, highlighting key differences that allow cellular networks to overcome the challenges of the physical environment.

a. Operating Frequency

Mobile phones in the United States operate at different frequencies based on carrier, uplink/downlink, and generation. In general, 2G and 3G cellular phones operate at 850 MHz uplink, and 1,900 MHz downlink with average transmission speeds of 0-5 Mbps. 4G cellular phones operate mainly at 1700 MHz uplink, and 2100 MHz downlink with average transmission speeds of 5-12 Mbps [17]. To compare to military-based operations, we overlay these frequencies and data rates on a chart displaying demonstrated throughput of the various MANET waveforms of interest (Figure 3-7) [18]. The 4G waveforms exist in a desirable section of the tradespace with higher data rates than achieved by both legacy and MANET waveforms, but in the same frequency range as both the SRW and WNW systems.

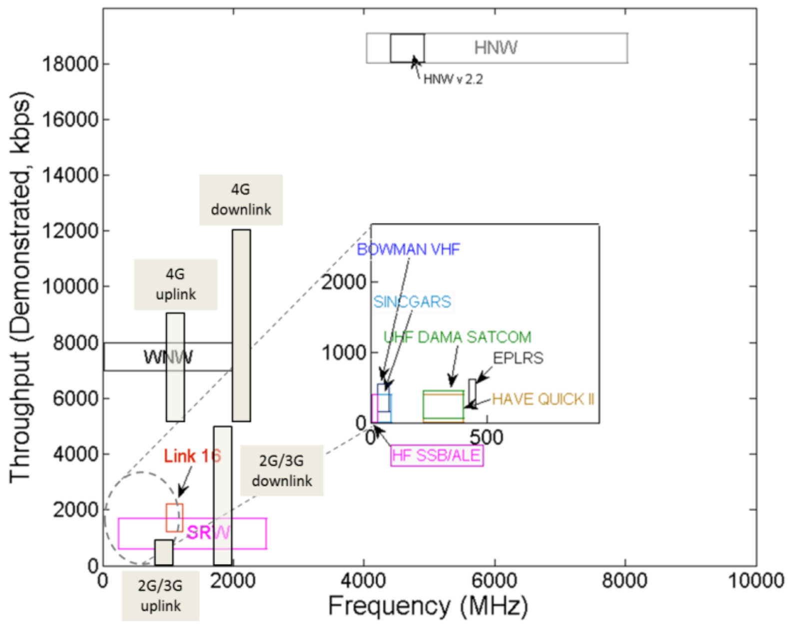

Figure 3-7. The Frequency and Demonstrated Throughput of JTRS, Legacy Waveforms, and Cellular Networks [18]

b. Infrastructure

The difference between MANET and cellular network throughput performance is predominately a product of infrastructure. Cellular networks are subdivided into a number of cells, each served by its own fixed base station tower (BST). Each BST is comprises a power amplifier, spectrum filters, control unit, transceivers, and a tower-mounted or elevated antenna. BSTs are not restricted by the size, weight, and power (SWaP) requirements of mobile radios, allowing them substantial flexibility in terms of antenna design, transmit power, and signal filtering equipment.

1) Transmit Power

Contrary to one's intuition, a cellular networks' downlink (tower to mobile radio) advantage is not derived from high transmit power. Although cell towers are capable of

transmitting at 100 watts or more, the power that they actually transmit is much less. For instance, a transmit power of 30-50 watts may be needed in rural locations, but power is typically limited to 10-20 watts in urban settings. Most cities now have a high density of towers that obviates the need for high-powered, long-distance transmissions. More importantly, “low” power transmission purposely limits each tower’s RF footprint, thereby allowing nearby cells to reuse the same transmission frequencies without interference. Since a BST’s transmit power is typically divided among multiple mobile users, the downlink power is actually quite comparable to that of a tactical radio (Table 3-1). Also, note that on the uplink, smartphones transmit at a maximum of only 500 mW (to minimize battery drain). This is considerably less than the lowest power setting of these tactical radios.

Table 3-1. Power and Antenna Specifications for Cellular Towers, Smartphones, and a Dismount Tactical Radio

Specification	**Cellular Tower** [19, 20]	**Smartphone** [21]	**AN/PRC-117G Manpack** [22, 23]
Transmit Power (W)	10-50	< 0.5	5-20
Antenna Height (m)	20-150	< 2	< 2
Antenna Gain (dBi)	17	≤ 0	-5

AN/PRC-117G Manpack dismount configuration specifications are shown. Antenna gain, listed in units of “dBi” or “decibels isotropic” is the gain relative to a lossless isotropic antenna.

2) Antenna Height

BST antennas are mounted on towers or building rooftops, 20-150 meters off the ground, making them less susceptible to line-of-sight blockages and Fresnel zone interference. Comparing these heights to a dismounted soldier’s radio (2-meter antenna height) or a tactical vehicle antenna (5 meters) shows that MANETs will experience considerably greater terrain attenuation and interference.

3) Antenna Gain

BSTs also offer ample space for large high-gain antenna designs that could never be accommodated on a mobile radio. “Gain” describes how well an antenna converts input power into radio waves and then directs them in a specific direction. A 0-dB gain antenna spreads the signal evenly upward, downward, and sideways, but a higher gain antenna flattens the omnidirectional pattern, as shown in Figure 3-8. A high-gain antenna increases the “effective power” of a radio – the power that is actually sent in the direction of the receiver. A typical tower-mounted antenna provides a huge gain (17 dB), but tactical radio antennas offer a relatively small improvement (1-5 dB) over the 0 dB antenna embedded in a smartphone. It’s important to note that because antennas have “reciprocity,” meaning their characteristics are the same whether transmitting or receiving, both the uplink and downlink signals benefit from the high gain antenna on the cell phone tower.

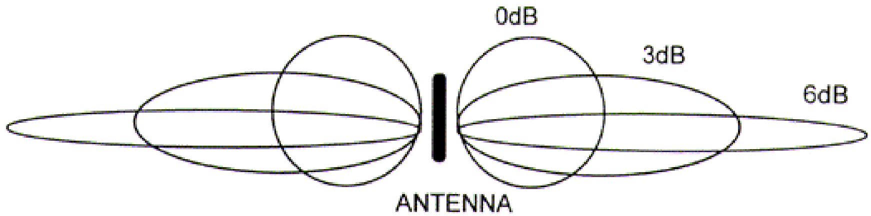

Figure 3-8. Schematic of Radiation Patterns for Antennas with Different Gains [24]

4) Base Station Subsystem Network Management

While BSTs are responsible for transceiving radio signals, ultimate control is held by a parent base station subsystem (BSS). The BSS monitors the link strength between mobile nodes and BSTs, allocates radio channels, and handles the call handovers from one BST to another BST. This offers two important advantages over a MANET: first, network management decisions are not the responsibility of mobile radio users, freeing up processing and energy resources on those devices; second and even more importantly, network management overhead (routing tables, network formation traffic, link state messages) are sent over back-haul lines between the BST and BSS, instead of consuming valuable throughput in the wireless network.

B. Power Consumption

Energy efficiency is a critical aspect of tactical radio performance for the dismounted soldier. Current soldier radio systems were not designed for minimum thermal signature, power efficiency, or low total energy consumption per mission; therefore, a typical soldier will carry 16 pounds of batteries for a 72-hour mission, often while facing harsh operating conditions, environments, and terrain. The requirements for the current software-defined radios' programs of record include specific soldier tactical-communications capability for a given battery but have not specified maximum energy usage per operation for those radios; therefore, developers of tactical radios have not been sufficiently motivated to keep up with commercial technology advances in power optimization. In his June 2014 memo, Major General McMaster recommended significant improvements be made to dismounted operation to solve battery and overheating issues before the Army fields any additional radios. He points to the fact that the software-defined HMS Manpack radio requires two batteries in its dismounted configuration to achieve an average of 6 hours of operation, but the older SINCGARS Advanced Special Improvement Program (ASIP) radio achieves an average of 33 hours of operation. He also reports that the radio reaches temperatures that make it unsafe for the warfighter to operate.

Although rapid battery consumption and device heating are listed as two separate complaints about the radio, device heating is an unfortunate but expected outgrowth of excessive power usage. These two symptoms of operational unsuitability indicate that the radios' difficulties come from a composite set of circumstances. The first is simply that the device *requires* too much power in certain scenarios. The second is that when

the radio is deployed in an operational scenario, it finds itself in a power-hungry state more often than was anticipated in the early stages of dismounted radio design. The third is that there appears to be no internal mechanism for the device to regulate itself (e.g., by recognizing that the battery is draining rapidly and self-heating is occurring, and adjusting in some way to stabilize power consumption). To circumvent this problem, the device would need to adapt its operating parameters in situ and scale back its performance temporarily rather than risk shutting off entirely from a fully drained battery. This would also eliminate the possibility of high currents causing permanent thermal damage to the hardware or, worst of all, inflicting harm on the soldier. This problem of unregulated power consumption creating an untenable situation for the warfighter is not restricted to SRW or the dismounted soldier: it is an ongoing frustration for WIN-T and mid-tier vehicular networking radios. The difference here is that the effect is more keenly felt because of the absurdity of the physical weight on the dismounted soldier, as well as the potential for bodily harm.

The instinctive solution to excessive power consumption by an electronic system is to develop hardware requirements that incorporate low-power circuit design along with battery improvements that increase capacity. But, in fact, the evolution of military tactical communications radio equipment into software-intensive devices means that optimizing the implementation of that software is a critical part of defining the equipment's power utilization. Ultimately, when a mobile node experiences poor reception due to RF isolation, as can be expected to occur in an operational environment, the radio will quickly consume as much power as it is given in order to grasp at connectivity. The operational suitability of the radio is contingent on its never being reduced to an unacceptable state of drained battery and excessive heat dissipation, even in extreme circumstances of isolation. This requires the radio to have the self-awareness to identify when it is in a state of high energy consumption; the algorithms that allow for the use of the absolute minimum power needed to accomplish each individual mission given the unique and dynamic set of circumstances; and the computational intelligence to use that information to regulate its own use of battery power and avoid overheating – all of which are currently missing from SRW.

In our simulations we observed that SRW nodes in the operational environment are consistently finding themselves in the category of "disadvantaged," or "isolated" with respect to their proximity to other nodes in the network, and their resulting link strengths. SRW nodes are therefore draining a great deal of power to simply "form" the network. Even if the network does converge to a stable state that requires less overhead and less power, any mobility within the network sends it into a state of reestablishing convergence all over again. The waveform does possess one capability that is intended to regulate the amount of power used based on the quality of a particular link, namely the adaptive transmission protocol (ATP.) However, it is not a requirement for an SRW radio to support this protocol, and we are confident that none of the radios running SRW during operational test were exploiting this waveform capability. The goal of ATP is to use the minimal amount of energy necessary to transmit the maximal data rate reliably across a

given link, which in theory could save power in the presence of strong links (such as for RF neighbors in very close proximity). However, it is also designed to ramp up transmit power levels to improve channel conditions between nodes, and further allow the radio to fall back to lower data rates in the presence of degraded channels. ATP would choose to minimize the power to transmit for a given condition but, in reality, would only rarely be finding the conditions for maximal data rate at low power for a link within RF range in any operational scenario.

To minimize the effects of weak links on power consumption, it is necessary to reduce the SRW routing algorithm's tendency to persistently negotiate connections with disadvantaged nodes, particularly in operational scenarios where those routes are not essential or are unlikely to facilitate useful communication links. The current routing scheme results in very high battery consumption in exchange for little usable bandwidth, and begs for a more energy-conscious approach to optimizing network connectivity in operational scenarios. For example, the SRW already has one mode of operation (unused, but defined), which places a specific limit on its power consumption – namely Unattended Ground Sensor (UGS), which is required by the System Performance Specification (v. 1.9.3) to "include a power management to reduce battery consumption to support a mission life of 30 days." The software is therefore expected to be capable of using its knowledge of its own energy usage to adapt its sleep/wake cycling and limit the use of nonessential functions. If we can expand this control capability to the other, more complex modes of the SRW waveform including the SS mode, the number of batteries that the soldier would need to carry could be far fewer and more precisely estimated.

4. Testing Deficiency: SRW's EW mode

SRW's physical layer offers two primary communication modes of operation: combat communication (CC) mode and electronic warfare (EW) mode.[1] CC mode is optimized for an uncontested electromagnetic environment where the warfighter desires high-spectrum efficiency and data throughput. EW mode, alternatively, is optimized for a hostile environment where the warfighter requires enhanced jamming protection, LPI, and LPD but is willing to accept a significant reduction in spectrum efficiency and data throughput. Although both modes are implemented in the waveform, CC mode remains the predominant or, more precisely, the only focus of both operational testing and waveform development. We find these trends particularly concerning given the tactical importance of an anti-jamming (AJ) mode. The effectiveness of a non-AJ mode such as CC is directly tied to our dominance of the electromagnetic spectrum. If future conflicts are against a near-peer adversary or are in an urban environment rich in RF-interference, a non-AJ mode will struggle and with it our warfighters' ability to carry out their mission.

When the absence of SRW EW mode was questioned following NIE 14.1, "spectrum limitations" were provided as an explanation. Spectrum is without question a limited commodity, but it's unrealistic to expect this to improve in a conflict environment. The real issue is that EW's anti-jam capabilities come at the cost of poor spectral efficiency and low data rates. If SRW is tested in EW mode, the maximum possible data rates will be only a small fraction of those in CC mode. Given the terrain and overhead issues already challenging radio operation, tactical radio programs are presumably wary that EW could cripple the radio's performance. With these programs showing little interest in EW mode, this portion of the waveform has been relegated to an afterthought in testing and waveform development. Consequently, we recommend that the expectations for SRW anti-jamming protection be reevaluated and a new direction established.

In this chapter we begin with an overview of anti-jamming signal types. We will then compare SRW's CC and EW modes and highlight important differences between the modulation and performance of each. Building on this insight, we discuss how the EW mode's low data rates and poor spectral efficiency explain its absence from NIE and

[1] A third communication mode, Featureless LPI/LPD, is mentioned in SRW SPS v1.9.3 (28 May 2013) [10]; however, we have no evidence that it has been implemented in the waveform yet. Featureless LPI/LPD will "support covert operations using low probability of intercept/low probability of detection techniques." The SRW SPS states that both EW and Featureless LPI/LPD modes shall implement jam resistance and LPI/LPD techniques. The techniques that will be used for Featureless LPI/LPD (if it is eventually implemented) remain unclear.

other operational testing. Finally, we discuss several future directions for an EW capability in the SRW.

A. Spread-Spectrum Anti-jamming Signals

Anti-jamming signals typically use a "spreading" process to transform the narrowband data signal into a wideband signal. Spreading can provide electronic protection in several forms:

- Resistance to narrowband interference
- Suppression of noise interference
- Low probability of detection
- Low probability of interception.

The two predominant spread spectrum modulations, Direct-Sequence Spread Spectrum (DSSS) and Frequency-Hopping Spread Spectrum (FHSS), are described in the following sections.

1. Direct-Sequence Spread Spectrum

DSSS is the spread-spectrum modulation utilized by SRW's EW modes, as well as two CC configuration (each mode has several configurations). DSSS takes a narrowband signal and multiplies it by a pseudo-random (PN) noise code "spreading" the original signal over a very large bandwidth. The spread operation transforms one bit of data into one or more "chips," which contain the original data bit and a redundant bit pattern. When the wideband signal arrives at the receiver, the original narrowband signal is recovered using the same PN code to "de-spread."

The value of DSSS lies in its wideband signal. Jamming at a narrowband frequency only affects a small fraction of the transmitted signal, leaving the vast majority of the transmitted signal unperturbed and increasing the likelihood that lost data can be reconstructed. An additional benefit of DSSS is that the signal energy at any particular frequency is as small as the thermal noise level, if not smaller. This effectively hides the signal in the environment providing LPD.

These anti-jamming and LPD benefits come with two important costs: lower data rates and low spectral efficiency. The spreading operation increases the amount of data being sent (original data bits + redundant data bits), and although the spread data throughput is faster than the original data rate, the true data throughput rate (original data bits only) will be slower. Generally speaking, the data rates achieved with DSSS will inversely scale with the amount of anti-jamming performance provided. Greater anti-jamming protection will come at the cost of lower data rates, unless the bandwidth of the spread signal is increased.

2. Frequency-Hopping Spread Spectrum

Although not currently employed in any SRW mode, FHSS is another spread-spectrum modulation, which may be incorporated into future updates. In FHSS, the

frequency of the narrowband signal is periodically changed, “hopping” the transmitted signal around the spectrum. The signal’s carrier frequency changes according to a pseudo-random “hopping sequence,” dwelling at each frequency for a short period of time, typically on the order of 100 ms. When the transmitted signal is regarded over longer periods of time, the hopping sequence effectively “spreads” the signal into a wideband signal. Redundancy and error correction can be achieved by executing re-transmission of the same data bit on different frequency hops.

In terms of anti-jamming capability, FHSS provides an effective countermeasure to narrowband, tone, and, depending on the dwell time, frequency follower jamming. Shorter dwell times provide greater jamming resistance, but, since more time is spent hopping, shorter dwells also decrease the amount of data that can be sent.

Another benefit of FHSS is LPI, as an adversary will have difficulty intercepting the transmission because of the pseudo-random nature of the hopping pattern. Unlike DHSS, where the spread-spectrum signal may sit below the noise floor, the clear narrowband spikes of FHSS will not be hidden from the enemy.

B. SRW Modes

Spread-spectrum modulation is incorporated into both CC (some configurations) and EW (all configurations) with the important distinction between these modes being the degree of spreading and, therefore, the degree of protection against jamming that they provide. In this section we highlight key differences in their performance in the presence of jamming, throughput, and spectral efficiency.

1. Combat Communication (CC)

CC mode can be utilized in four different configurations (shown in Table 4-1), all using 1.2 MHz of bandwidth. Configuration 1 is a non-spread modulation, which provides the highest data throughput of any configuration (in either CC or EW modes). Configuration 2 is also non-spread but provides increased robustness due to greater error encoding. Configurations 3 and 4 are DSSS spread modulations, but the degree of spreading is relatively small, and thus the AJ protection is limited.

Table 4-1. CC Mode Configuration Specifications

CC Configuration #	BW (MHz)	Spread (Chips/Symbol)	Theoretical Data Rate (kbps)
1	1.2	1	2000
2		1	936.6
3		8	112.5
4		16	56.25

Note*:* One symbol is composed of 1 or more data bits and 1 or more error code bits.

2. Electronic Warfare (EW) Mode

SRW documentation describes EW mode as having 28 different configurations (Table 4-2) with bandwidths ranging from 0.5 MHz to 32 MHz. At each bandwidth four different configurations each provide a different degree of DSSS modulation (more chips/symbol provides greater spread and AJ). The spreading modulations for most EW configurations are substantially greater than those in CC mode, providing a true anti-jam capability.

Table 4-2. EW Mode Configuration Specifications

EW Configuration #	BW (MHz)	Spread (Chips/Symbol)	Theoretical Data Rate (kbps)
1	32	8	3000
2		16	1500
3		32	500
4		128	125
5	16	8	1500
6		16	750
7		32	250
8		128	62.5
9	8	8	1500
10		16	375
11		32	125
12		128	31.25
13	4.8	8	900
14		16	225
15		32	75
16		128	18.75
17	2.4	8	450
18		16	112.5
19		32	37.5
20		128	9.38
21	1.2	8	225
22		16	56.25
23		32	18.75
24		128	7.03
25	0.5	8	46.88
26		16	15.63
27		32	5.86
28		128	1.95

Note*:* One symbol is composed of one or more data bits and one more error code bits.

It's important to note, however, that this robustness comes at great cost – in the form of significantly reduced data rates and/or dramatically increased bandwidth requirements. For instance, the SRW mode most widely used in operational test, CC configuration #2, offers a max theoretical data rate of 937 kbps at 1.2 MHz bandwidth. In EW mode, obtaining just 900 kbps of throughput (using configuration #13 – with 8 chips/symbol), requires a minimum of 4.8 MHz of bandwidth per channel!

If we consider a channel bandwidth equal to that used in CC mode (1.2 MHz), the highest data rate possible in EW is 225 kbps (configuration #21), more than a factor of 4 drop from CC configuration #2 (937 kbps)! Note that of the 1.2 MHz EW mode configurations (#21-24), configuration #21 (225 kbps) is the least "spread" configuration. If greater AJ protection is required, the throughput performance becomes even worse. With spectrum limited in most environments, the implications of choosing EW mode are clear: expected data rates will be significantly less than those in CC mode.

C. The Absence of SRW EW Mode at the NIE

SRW's EW mode has been absent in operational testing. The "EW" testing that takes places is invariably the introduction of threats, namely a simulated adversary performing electronic warfare attacks against SRW but does not require that the EW mode of SRW be available to the soldier. SRW development, including the development of an EW mode, has been ongoing for many years, yet this important capability remains on the sidelines during test, largely because the programs of record lack a specific requirement for testing it. In fact, of all the modes and configurations, operational testing continues to focus on a single configuration – CC configuration #2 (937 kbps, non-spread modulation), with no attempts to demonstrate other CC modes, or any of EW mode's 28 configurations. The continued use of this CC mode during "electronic warfare" testing at NIE is difficult to justify, considering that an extensively developed mode, specifically designed for those scenarios, already exists. Either electronic warfare is concerning enough that a protective mode is needed, or it is not concerning – in which case the electronic warfare attacks conducted in operational test are superfluous. We argue that although it is universally accepted that an EW mode is essential, the limitations of the waveform make operating it impractical – and that is why it is avoided in OT.

1. Are "Spectrum Limitations" in Operational Test to Blame?

When the absence of SRW EW mode was questioned following NIE 14.1, "spectrum limitations" were blamed, i.e., the bandwidth available for EW operation was insufficient. To investigate this claim we analyzed spectrum allocation during NIE testing.

SRW is designed to operate at frequencies in the 225-2500 MHz range. The Department of Commerce allocates approximately 30 percent of this spectrum band for exclusive Government use, of which a smaller subset is available for NIE testing. During NIE tests 13.1, 13.2, and 14.1, SRW channels were confined to five spectrum blocks:

UHF-1 (225-306 MHz), UHF-2 (307-378 MHz), UHF-3 (379-450 MHz), lower L-band (1,350-1,390 MHz), and upper L-band (1,755-1,850 MHz). For NIE 14.1, UHF-3 was specifically allocated for Enhanced Position Location Reporting System (EPLRS) testing and was not available for SRW use. If we make the conservative assumption that UHF spectrum outside of these blocks was allocated for other testing/non-Government use, this restricts our spectrum allocation analysis to the UHF band (225-378 MHz) and L-bands (1,350-1,390, 1,755-1,850 MHz). In addition to SRW channels, these spectrum bands also support channels from other waveforms and devices [Adaptive Networking Wideband Waveform 2 (ANW2), etc.].

Figure 4-1 shows the bandwidth used by SRW and the other waveforms at NIE 14.1 in the spectrum bands defined above. Thirty-six SRW channels (1.2 MHz bandwidth each, in CC mode), occupy approximately 43 MHz of bandwidth. The unallocated bandwidth is shown in the hashed purple region and represents a sizeable chunk of the spectrum blocks. Combining this free spectrum with the SRW allocated bandwidth, gives a total of 146 MHz available for SRW use in the UHF band and 75 MHz available in the L-band. While this estimate represents an upper bound on spectrum availability, it nonetheless indicates that "spectrum limitations" weren't quite as dire as they were portrayed to be.

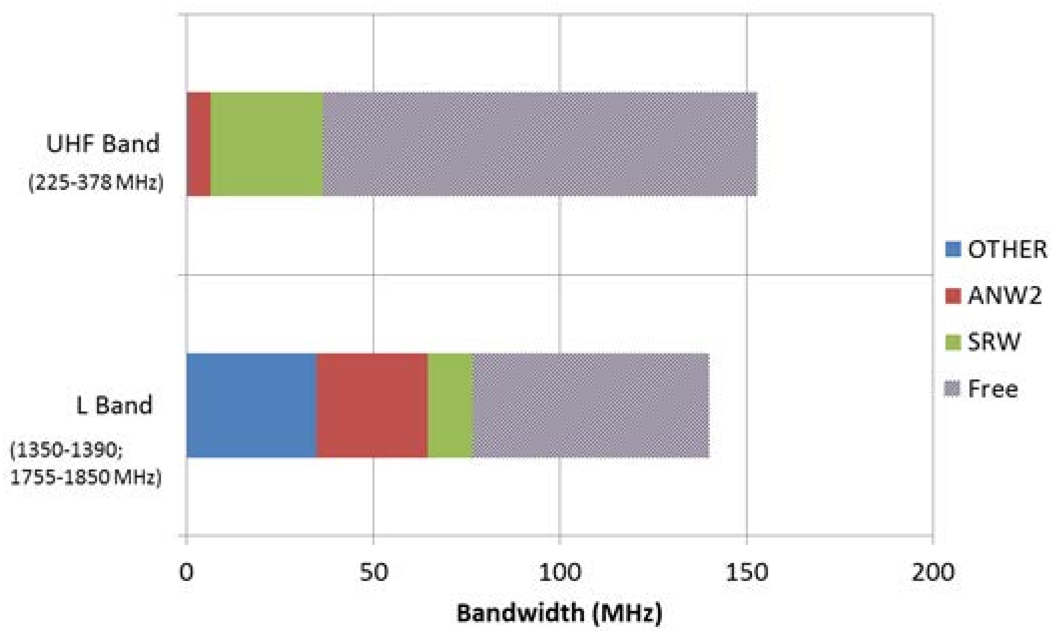

Figure 4-1. Spectrum Allocation at NIE 14.1

Operating the same number of SRW channels (36, at a 1.2 MHz bandwidth) in EW mode would have been possible, but these channels could have only supported 25 percent of the data rates possible in CC configuration #2. To achieve data rates similar to those in CC configuration #2, EW configuration #13, with its 4.8 MHz bandwidth channels, would have been required. In this case, four times as much bandwidth is needed, in which case spectrum limitations would indeed have been a major concern.

The lack of available spectrum is further exacerbated by SRW network architecture. In our discussion of SRW's network design vs. its implementation, we describe how testing has shown that SRW overhead becomes unmanageable as the network scales beyond 30 or so nodes. To alleviate this issue, NIE network planners assigned one UHF channel to the company level and one L-band channel to each of the platoons. As a result, a network that was originally envisioned to occupy two 1.2 MHz channels (one each for tier 1A and tier 1B), now takes four, doubling the spectrum requirements.

2. The Fundamental Problem with EW Mode Operation

RF spectrum is heavily controlled in an operational test – such dominance is unlikely to exist in an overseas conflict, so limited spectrum will be an important consideration for any environment. Because of these constraints, SRW EW mode operation will be restricted to its lowest bandwidth configurations, and therefore the expected data rates will be a small fraction of those in CC configuration #2. Given the terrain and overhead issues already challenging CC mode operation, it appears tactical radio programs are in silent agreement that operating EW mode under the same conditions will result in little to no successful transmission of data. The bottom line is that EW mode's poor spectral efficiency and low data rates are preventing it from ever entering operational testing. Because including the mode has not been mandated, this portion of the waveform has been relegated to the sidelines of testing and waveform development. The expectations for SRW anti-jamming protection must be reevaluated and a new direction established if the waveform is to provide adequate protection to the warfighter in hostile environments.

D. What Is the Future Direction for SRW Electronic Warfare?

Any electronic-warfare-enabled waveform will face the inherent tradeoffs that come with spread-spectrum modulation – improved anti-jamming, LPI, and LPD capability at the expense of increased bandwidth and reduced data rates. This tradeoff is even more challenging for a waveform like SRW, which struggles to meet data throughput requirements in its normal mode of operation. Asking SRW to achieve the same system performance in a spread modulation is an unrealistic expectation. The future of SRW EW will necessarily require some compromises on network size, number of participants, and the type and quantity of traffic messages that will be transmitted.

In this final section of the chapter, we highlight several science and technology (S&T) development efforts that appear to be trending in this direction. These proposals seek to incorporate some degree of electronic warfare capability in to CC mode. In addition, we note a development effort focusing on EW mode itself, which looks to improve performance by incorporating significant advances that have been used by the wireless industry over the past 20 years.

1. Ongoing Development of SRW EW Capabilities and OFDM Modulation in CC Mode

U.S. Army Research, Development, and Engineering Command (RDECOM) Communications-Electronics Research, Development and Engineering Center (CERDEC) is developing a new SRW electronic warfare capability that will be supported in CC mode only. This effort, referred to as "SRW EW-Comms (EW-C)" would provide AJ protection and LPI through frequency-hopping spread spectrum rather than DSSS modulation. This capability seems to be targeted as an electronic warfare improvement for critical communications – PLI and Voice only. Expanding this function beyond these small traffic loads will not be easily realized. Initial lab testing has successfully demonstrated PLI and voice traffic on an 18-node network, but throughput performance remains an issue even in this new implementation.

Limiting electronic warfare capabilities to critical communications is a sensible course of action, though a similar path may have been possible using the current EW mode. The rationale behind the decisions to develop this capability outside of EW mode, and to use FHSS in lieu of DSSS, remains unclear.

A second modification which may be incorporated into CC mode is Orthogonal Frequency Division Multiplexing (OFDM), a modulation employed by many modern wireless system standards including WiFi (802.11a-n), WiMAX, and 4G LTE. OFDM is also employed by the WNW in its primary mode of operation.

Sometimes considered a spread-spectrum modulation, OFDM is a form of multicarrier modulation that divides the original data signal among many closely spaced subcarrier signals. Normally in Frequency Division Multiplexing (FDM), carrier signals must be adequately spaced apart to prevent their sidebands from overlapping and causing interference. In OFDM, the subcarrier frequencies are chosen such that they are orthogonal to one another, thereby eliminating sideband cross-talk.

The advantages of OFDM include:

- *Spectral efficiency* – As result of their "orthogonality," the subcarrier signals can be grouped closely together, making OFDM a highly spectral efficient modulation.
- *Multi-path resistance* – The individual subcarriers transmit data at slower data rates, such that symbol period is longer than multipath delay spread, allowing OFDM to resist multi-path interference.
- *Narrowband jamming resistance* – If a particular subcarrier frequency experiences strong interference, that channel can be shut down, reducing the effect of narrowband jammers.

There are several important disadvantages to OFDM as well:

- *Poor power efficiency* – OFDM requires a RF amplifier that operates in the linear regime. This is bad news for power-challenged radios like Rifleman

Radio because non-linear operation offers the highest energy efficiency. The effect of OFDM's higher power consumption is mitigated in 4G LTE operation where OFDM is used for downlink (tower to mobile phone) while single carrier Frequency Division Multiple Access (FDMA) (non-linear amplifier compatible) is employed in the uplink (mobile phone to tower).

- The orthogonality requirement makes this technique much more sensitive to frequency offset resulting from system sensitivity/drift, Doppler effect, etc.
- This method does not provide low probability of detection – subcarrier signals are clearly transmitted above the thermal noise floor.
- Static frequency assignments are more susceptible to jamming and interception than frequency-hopping modulation.

An OFDM CC mode would likely only offer modest AJ protection as it is not a true spread modulation. It's interesting to note that WNW, which uses OFDM in its normal mode of operation, does not use OFDM for its AJ operation. Instead it has a separate mode that employs a combination of DSSS and FHSS.

2. Performance Improvements to EW Mode

A large gap exists between SRW EW mode's SNR specification and the theoretical SNR limit (Shannon capacity), suggesting that there is significant opportunity for performance improvement. A new initiative looks to capture some of this performance potential by incorporating significant advances that have been used by the wireless industry over the past 20 years. Initially this work is focused on replacing EW mode's convolutional encoder with a more efficient turbo encoder such as that being used by 4G LTE. This work could potentially pay off with increases in SNR sensitivity, enabling higher data rates for a given level of anti-jam resistance.

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5. Conclusions

Observations of SRW in operational test environments have revealed many challenges to the development and fielding of systems using this waveform. We have taken an analytic approach to understanding the core causes for the symptoms seen in OT, which include poor range, excessive power consumption, and high management demands.

First we evaluated the waveform as it was designed and compared it to the topology used in the Network Integration Exercises, finding fundamental differences. We identified poor RF link quality and excessive rates of overhead network traffic as the driving factors in developing the current architecture (as opposed to operational need) and used modeling and simulation to explore the traffic rates as a function of the topology and environment. We noted specific ramifications on network connectivity and convergence times.

In addition, we found that the poor scalability of SRW due to overhead severely limited its ability to behave as an ad hoc network, thereby obviating the need for many of the complicating MANET features in the waveform design. Our simulations show that terrain interference and low node density can create overhead traffic levels that equal or exceed network data traffic demands. Even over the mild terrain of WSMR, attenuation and multipath interference is great enough to degrade signal strength and influence overhead message traffic. Reduced node density makes these terrain-degraded links even more tenuous by increasing the separation between nearest neighbors and decreasing the number of routing pathways. It also interferes with the convergence of the network to a stable state and forces it to constantly expend computational resources on neighbor discovery and link optimization.

A true solution to SRW's overhead problem, as it relates to network scaling, would require a new approach to MANET design and a complete overhaul of the waveform. The seemingly less drastic approaches we have been able to identify (changes to topology and pared down functionality) make the system far less worthwhile to the soldier.

We used M&S to demonstrate the unique point-to-multipoint broadcast behavior of SRW CNR calls, highlighting how terrain and sparse network design can affect call performance. For a dense network, where many relay routes exist, we described additional concerns related to SRW's "adaptive equalizer." IDA recommends a more

detailed review of this capability, provided that more detailed information regarding the algorithm and its implementation on specific radio systems could be made available.

The lack of robust network operation is at its most basic a failure of consistent radio connectivity. We reviewed the effects that the physical environment (due to attenuation) has on radio communications and evaluated specific failures seen at NIE 14.1, referred to as the CACTF attack. Even in benign, open desert conditions, the effects of terrain are considerable and limit the range of communication. Even at short ranges, we found that attenuation due to urban structures may have been sufficient to degrade the signal below a minimum threshold of usability, although without a direct measurement, other causes of failure cannot be ruled out. We also explored the effect of the operational environment on power consumption, finding that there may be software-based mitigations to the many power issues seen in OT. These approaches, which are commonly seen in modern electronics design, do not appear to be a priority or a requirement for radio programs of record.

Finally, we highlighted a significant testing deficiency: the lack of testing of SRW's EW mode. We concluded that the offered explanation – limited spectrum availability at the NIE – is an unlikely excuse for this mode to remain untested in OT. Instead, the difficult compromises in network size, number of participants, and the type and quantity of traffic messages that can be transmitted in SRW's EW mode need to be addressed and should not be delayed any longer. While investigating the original claim that spectrum is to blame, we found that spectrum utilization and management does indeed pose another significant obstacle to successful fielding of the Army's network, but that is independent of the EW mode implementation or testing. "Limited spectrum" at the NIE and difficulties managing its allocation should not be expected to disappear in an overseas conflict. If anything, the levels of spectrum dominance enjoyed in OT are unlikely to exist – which indicates that the spectrum problem can only get worse.

We believe this analysis, which merges modeling and simulation of waveform behavior with an analysis of the physical constraints of the operating environment, maps the vast majority of the issues reported, including lack of connectivity, throughput, excessive power consumption, limited spectrum availability, and increased network planning burdens to the SRW waveform itself. We have identified shortcomings of the waveform, as well as disparities between the waveform's original concept and its implementation on specific radio platforms and in specific network topologies. By identifying the fundamental constraints in the interplay between network behavior and physical layer connectivity, we present a better set of expectations for how far the current waveform technology can advance the Army's vision of network modernization. Any "fixes" to the radio or the waveform henceforth proposed or promised should spur a similarly rigorous examination of the effect on network performance in light of the terrain, mobility, power, and EW realities facing the warfighter.

Appendix A
List of Illustrations

Figures

Tables

Appendix B
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Appendix C
Acronyms and Abbreviations

3D	three dimensional
4G	4th Generation
AGI	Analytical Graphics, Inc.
AJ	anti-jamming
AMF	Airborne, Maritime, Fixed Station
ANW2	Adaptive Networking Wideband Waveform
ASIP	Advanced Special Improvement Program
ATP	adaptive transmission protocol
BMC	Brigade Modernization Command
BSS	base station subsystem
BST	base station tower
C4	command, control, communications, and computers
CACTF	Combined Arms Collective Training Facility
CC	combat communication
CERDEC	Communications-Electronics Research, Development and Engineering Center
CNR	Combat Net Radio
DARPA	Defense Advanced Research Project Agency
dB	decibel
DES	Discrete Event Simulation
DISA	Defense Information Systems Agency
DSSS	Direct-Sequence Spread Spectrum
DTED	Digital Terrain Elevation Data
EPLRS	Enhanced Position Location Reporting System
EW	electronic warfare
EW-C	SRW EW-Comms
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
FOT&E	Follow-on Test and Evaluation
FSPL	free space path loss

GD	General Dynamics
GHz	gigahertz
H_2O	water vapor
HMS	Handheld, Manpack and Small-form Fit
I/Q	In-phase and Quadrature
IER	Information Exchange Requirement
IMS	Intelligent Munitions Systems
IP	Internet Protocol
IR	Information Repository
JCSS	Joint Communication Simulation Software
JNMS	Joint Network Management System
JTNC	Joint Tactical Networking Center
JTRS	Joint Tactical Radio System
kbps	kilobits per second
km	kilometer
km^2	square kilometer
LPD	low probability of detection
LPI	low probability of intercept
LS	Launch System
LSA	Link State Advertisement
M&S	modeling and simulation
MANET	mobile ad-hoc network
Mbps	megabits per second
MCoE	Maneuver Center of Excellence
MHz	megahertz
MIT	Massachusetts Institute of Technology
MNVR	Mid-tier Networking Vehicular Radios
Msps	megasamples per second
MUOS	Mobile User Objective System
mW	milliwatt
ND	Neighbor Discovery
NIE	Network Integration Evaluation
NLOS	Non-Line of Sight
O_2	oxygen
OFDM	Orthogonal Frequency Division Multiplexing
OPNET	Optimum Network Performance
OSPF	Open Shortest Path First
OT	operational testing

PDSU	Positional Dismounted Soldier Unit
PLI	Position, Location Information
PN	pseudo-random
ppm	parts per million
PROP	Packet Radio Organizational Packet
PTT	push-to-talk
RDECOM	Research, Development, and Engineering Command
RF	radio frequency
S&T	science and technology
SALT	Small Airborne Link 16 Terminal
SANR	Small Airborne Networking Radio
SDD	Software Design Description
SDR	software-defined radio
SINCGARS	Single-Channel Ground-to-Air Radio System
SNDCF	Subnet-Dependent Convergence Function
SNR	signal-to-noise ratio
SPEED	Systems Planning, Engineering and Evaluation Device
SRW	Soldier Radio Waveform
SS	Soldier System
STD	Software Test Description
STK	Satellite Toolkit
SWaP	size, weight, and power
TAPETS	The ATEC Player and Event Tracking System
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TIREM4	Terrain Integrated Rough Earth Model v4 (
UGS	Unattended Ground Sensor
UHF	ultra high frequency
VCXO	Voltage Controlled Crystal Oscillator
VHF	very high frequency
VRAP	Voice Resource Allocation Packet
WDS	Waveform Design Specification
WIN-T	Warfighter Information Network–Tactical
WNAN	Wireless Network After Next
WNW	Wideband Networking Waveform
WSMR	White Sand Missiles Range

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Appendix D
SRW Message Load Requirements for SS Domain [10]

Msg Type	Range of Msg Size or Duration	Service UC MC BC	Message Requirements by Echelon (Message Size is in (Bytes) or Duration(Sec)),							
			Battalion (8 Voice Nets) 129 radio nodes		Company (9 Voice Nets) 45 radio nodes		Platoon (27 Voice Nets) 207 radio nodes		Squad/Team (51 Voice Nets) 423 nodes	
			Avg Msg Size/Duration	Msgs per hour	Avg Msg Size/Duration	Msgs per hour	Avg Msg Size/Duration	Msgs per hour	Avg Msg Size/Duration	Msgs per hour
Data	1-20 KB	BC	1.13	486	5	.75				
KBytes	5-50 KB	MC	10	2	5	3.75	27.5	30	31.4	261
	2-50 KB	UC	8.9	22			20.9	63.75	35	243
Video 256 kbps	1-15 min	MC	10	.4			5	3.75	8	18
	.5-60 min	UC	26.9	18	60	1.5	3.7	11.25	37.5	18
Video 16/64 kbps	15 min	MC			15	.75	15	3.75	15	18
	1-60 min	UC	60	2	60	1.5	60	3.75	6.5	36
Still Image KByte	50-2500	MC	500	2			617	22.5	52	2169
	50-2500	UC	402	38			458	22.5	1017	27
Net Voice Seconds	1-27 sec	MC	4	3600	4	2700	4	4860	4	4590
				50% duty cycle		33% duty cycle		20% duty cycle		10% duty cycle
SA Up every 12 seconds	.128 KB	UC	.128	38,700	.128	13,500	.128	62,100	.128	126,900
SA Dwn every 12 seconds	5 KB	MC	5	2400	5	2700	5	7200	5	10,800
Multimedia 75 kbps Collab Plan Minutes	1-60 min	MC	15	.25	5	.25	5	.25		

UC: Unicast, MC: Multicast, BC: Broadcast

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Miriam S. Marwick, Project Leader

14. ABSTRACT

In this report, we present the results of our modeling and simulation of SRW, which we use to explain the root causes of the problems that we have seen surface in operational test. Our analysis merges modeling and simulation of waveform behavior with an analysis of the physical constraints of the operating environment. We used our observations from the Network Integration Exercises (NIEs) to construct representative scenarios for simulation and to configure the SRW nodes according to the Army's implementation. We found that many of the difficulties encountered in testing the network and in achieving desired performance can be traced to discrepancies between the Army's use of SRW and the original concept with which the waveform was designed.

15. SUBJECT TERMS

Tactical Networks, Waveforms, Software Defined Radios, Cognitive Radios, Warfighter Communications, Electronic Warfare, Operational Testing

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